The efficiency of voice production

H.K. Schutte

Rijksuniversiteit te Groningen

The efficiency of voice production

Proefschrift

ter verkrijging van het doctoraat in de Geneeskunde
aan de Rijksuniversiteit te Groningen
op gezag van de Rector Magnificus Dr. J. Borgman
in het openbaar te verdedigen op woensdag 7 mei 1980
des namiddags om 2.45 uur precies

door

Harm Kornelis Schutte
geboren te Hasselt (Ov.)

Druk: Kemper/Groningen

Promotores:
Prof. Dr. Jw. van den Berg
Prof. Dr. P.E. Hoeksema

Stellingen

behorende bij het proefschrift
The efficiency of voice production
door H.K. Schutte

Groningen, 7 mei 1980

1 De door Kunze geformuleerde opvatting dat de subglottische drukmeting met behulp van de druk in de slokdarm volgens de door van den Berg aangegeven methode niet bruikbaar zou zijn, berust op verkeerde interpretatie van longfysiologische gegevens.

L.H. Kunze, Ph.D. Thesis Iowa, 1962

2 De procedure bij aerodynamische metingen om te onderzoeken personen "vrij te laten foneren", is acceptabel voor wat betreft de keuze van de toonhoogte, maar leidt tot niet representatieve gemiddelde waarden van subglottische druk en flow als functie van de geluidssterkte.

3 Bij patiënten met chronische laryngitis of leukoplakische veranderingen van de stemplooien dient meer dan tot nu gebruikelijk, aandacht besteed te worden aan de inspanning waarmee de stem geproduceerd wordt. Een nauwe samenwerking tussen foniater, KNO-arts en (klinisch) logopedist is daartoe vereist.

4 Bij het normaliseren van gegevens over de individuele stemmogelijkheden (fonetogram), zoals door Coleman c.s. is gedaan, gaat veel voor het individu relevante informatie verloren.

R.F. Coleman, J.H. Mabis en J.K. Hinson: J Speech Hear Res, 20, 197-204, 1977

5 De kwaliteit van de stem na behandeling van een beperkt stemplooicarcinoom met de CO_2 laser is gewoonlijk minder fraai dan na een radiotherapeutische behandeling.

6 In de bedrijfsgeneeskunde wordt te weinig aandacht besteed aan de invloed van industrielawaai op het gebruik van de stem en de daarmee samenhangende gezondheidstoestand van de larynx.

E. Rontal, M. Rontal, H.J. Jacob en M.I. Rolnick: Ann Otol Rhinol Laryngol, 88, 818-821, 1979

7 Bij een patiënt met afasie moet routinematig een audiologisch onderzoek plaats vinden.

8 Voor een juiste indicatiestelling tot het doen van een pharynxplastiek bij jonge kinderen moet een zorgvuldige afweging worden gemaakt tussen de invloed van de nog in ontwikkeling zijnde articulatie en de onvolkomen werking van de velopharyngeale sphincter.

9 In het belang van de patiënt dient een duidelijk onderscheid gemaakt te worden tussen taalontwikkelingsstoornissen en gestoord geraakte taalfunctie (afasie).

S.M. Goorhuis-Brouwer, Niet-vanzelfsprekend. Orthovisie nr. 10, Wolters-Noordhoff 1979

10 Voor de discussie over gemeentezang: wijze van zingen, klankkleur en timbre, tempo en verdere culturele implicaties, is het wenselijk dat een historisch, eventueel metabletisch onderzoek gedaan wordt naar het gebruik van de menselijke stem in vroeger tijden, in het bijzonder tijdens de kerkdiensten.

11 De bezwaren tegen re-implantatie van pacemakers zijn in hoofdzaak gebaseerd op emotionele en niet op medisch-technische gronden.

12 De term psychogeen in het verband "psychogene stemstoornis" dient ruim opgevat te worden, in die zin, dat met deze term wordt aangegeven dat de emotionele instelling van personen de stemgeving in hoge mate beïnvloedt, zowel bij psychisch gezonde, als psychisch gestoorde personen.

13 Een psychogene afonie betekent vaak een ingehouden kreet om hulp.

14 In het algemeen valt aan de spreektoonhoogte van co-assistenten waar te nemen dat met het stijgen op de maatschappelijke ladder de gemiddelde spreektoonhoogte daalt.

15 De stikker achter op auto's "Neem gas terug" kan tijdens het rijden alleen worden gelezen wanneer flink gas wordt gegeven.

Acknowledgements

The following persons, each in their own way, have contributed to my training and the performance of this study. I would like to express my appreciation and gratitude to all of them. I thank:

-- Prof. Dr. Jw. van den Berg, for his guidance and advice and his teaching of voice physiology. I always will remember his stimulating personal lessons on this subject;

-- Prof. Dr. P.E. Hoeksema, Director of the ENT-Department. In his clinic I got the berth for studying voice and speech pathology;

-- Mr. E. Th. Edens (M.D.; ENT-Surgeon), for his essential contribution in the direct measuring of the subglottic pressure;

-- Mr. J.H. van Dijk, for his skilful effort in preparing the computer programmes and in controlling the computer devices in the Institute of Audiology;

-- Messrs. P.H.C. Jongschaap, J.A. van de Vliet, C.A. van Donselaar and J.D. van Houdt, for their appreciated assistance during the investigations;

-- The staff of the Department of Phoniatrics and Logopedics who not only acted in this study as trained listeners, but also deserve thanks for their help in many other ways. Mrs. S.M. Goorhuis-Brouwer for her stimulating remarks in our discussions on some points in the manuscript;

-- Mrs. J.M. Wilkens-Gietema, who not only carefully typed several stages of the manuscript, but also, in fact, effectuated the final lay-out;

-- Mr. M. Goslinga, for his meticulous preparation of the photographs and figures;

-- Mrs. D.J. Niermeyer, for her bibliographic assistance;

-- Mr. V.J. Fidler (M.Sc.) of the Centre for Medical Data Processing and Statistics, for his advice on statistics;

-- Messrs. G.G. Bergink (M.D.), and Prof. Dr. D. Graham Stuart of the Groningen University Institute of Phonetic Sciences, for translating and perusing the text;

-- The staff of the Department of Medical Photography (Head: Mr. J.M. Martens), for making the photographs of the measuring equipment;

-- The co-workers of the electronic workshop of the Groningen University Laboratory for Medical Physics, Head: Mr. F.G.J. Swarte, and E. Albronda, F. Berg, G.J.J. Bonga, and of the Institute of Audiology, H.S. Freye, and of the technical service of the ENT-Clinic, K. Kuitert, G.T. Prins, A. de Jong, for their valuable assistance;

-- The normal subjects and the patients. Without their co-operation our investigations could not have been executed;

-- All those, whose names have not been mentioned and who assisted in short and long lasting discussions.

This study has been elaborated in the Ear, Nose and Throat Clinic (Professor Dr. P.E. Hoeksema), and the Department of Phoniatrics and Logopedics of the State University Hospital in Groningen.

The investigations have been executed in close co-operation with the Groningen University Laboratory for Medical Physics (Professor Dr. Jw. van den Berg), in one of the laboratory rooms in the Institute of Audiology (Professor Dr. R.J. Ritsma) of the State University Hospital in Groningen.

For the translation financial support has been received from the "Prof. Dr. Eelco Huizinga Stichting".

We also gratefully accepted a grant from the "Jan Dekker Stichting" and the "Dr. Ludgardina Bouwman Stichting" for the reproduction of some coloured figures, and from the "Scholten-Cordes Fonds".

To my wife JENNY
and our children

Psalms

I will sing unto the Lord as long as I live;... *104: 33a*

...; sing unto the Lord, all the earth. *96: 1b*

Contents

Chapter 1 Introduction

The human voice may well be considered to be the main mean of expression of mankind. Human beings not only possess the unique gift of spoken language, they also can express emotions, thoughts and observations in a variegated and personal way.

The voice provides the acoustical basis of communication via spoken language, by which people may acquire knowledge and organize their thoughts and picture of the world. Language also serves as the medium by which civilization is transferred from generation to generation and diffused geographically.

Vocal sound, needed for speech, is produced in the larynx. This basic sound is modelled by the acoustical properties of the vocal tract into the perceived vocal sound. The different speech sounds are formed by purposeful adjustment of the speech organs.

Communication via spoken language is hampered or even rendered impossible when the production of vocal sound causes problems.

A certain level of sound intensity is necessary for speech communication. Whether the sound intensity is sufficient or not, depends partly on the efficiency of the larynx as a sound source.

It may be expected that the efficiency of voice production is decreased in the case of patients with voice problems. Producing an adequate sound intensity then requires more than normal effort.

From the literature concerning voice production, it appears that so far no systematical investigation with respect to the efficiency of phonation has been carried out.

In view of the complexity of the physiology of phonation, it seems advisable to begin our consideration with a survey of the various physiological factors of importance. For a description of the anatomy of the larynx we refer to the standard manuals of anatomy.

The vibration of the vocal folds is induced by a complicated combination of aerodynamic, muscular, and elastic forces in the larynx.

According to the myoelastic-aerodynamic theory of phonation (van den Berg, 1958) the subglottic pressure is raised after the vocal folds have been adducted. When the subglottic pressure is high enough to overcome the resistance of the adducted vocal folds, these will diverge and air will escape via the glottis. Owing to the narrowing at the glottis the velocity of the air increases, resulting in a decreasing pressure in the glottis itself, caused by the Bernoulli effect. The decrease of the subglottic pressure as a consequence of the escaping of air via the glottis, the inwards sucking action by the Bernoulli effect on the vocal folds, and the elasticity of the vocal folds, result in their return to the midline position and (in chest register) closure of the glottis. If the subglottic pressure is again raised sufficiently high to divert the vocal folds, the vibration cycle starts once more. The resulting tiny bursts of air via the glottis constitute a source of sound, the frequency of which is determined by their rhythm.

The vocal folds are made to vibrate by a stream of air, but the pattern of vibration is primarily determined by laryngeal conditions. The adjustment of the larynx depends on the degree of contraction of internal and external laryngeal muscles. The innervation of these muscles, regulated by the central nervous system, guarantees control of tension and elasticity of the muscles.
In adjusting the contraction of these muscles before and during phonation, an important role is played by the action of a great number of mechanoreceptors. A survey of the neuromuscular regulation of phonation has been published by Wyke (1974a, b, c, d, 1976).

By changing the adjustment of the larynx the resulting vocal sound may be varied in pitch and intensity.

Intensity and timbre depend on the way in which the form and the area of the glottis change during the vibration cycle, i.e. the quality (timbre) of the voice depends on the glottal wave form. In addition the configuration of the vocal tract has an influence on the ultimate quality of the sound.
In chest register the glottis is open during a part of the vibration cycle and remains closed during the other part. The fraction of the time during which the glottis is open during the vibration cycle has been called "open quotient". Air can only escape during the open phase. Therefore the flow i.e. the volume of air per unit of time passing via the glottis, seems to be an important criterion for the function of the larynx.

The volume of air allowed to escape per vibration cycle also depends on the adjustment of the laryngeal muscles. This adjustment determines the necessary height of the subglottic pressure required to open the glottis. The sensitive mechanoreceptors in the subglottic space react to tissue traction, responding to the subglottic pressure and thus contribute to the regulation of phonation.

For a more extensive description of the myoelastic-aerodynamic theory of voice production and other aspects of vocal physiology and speech we refer to publications of van den Berg (1958, 1968), and manuals of e.g. Minifie, Hixon, and Williams (1973), and Hardcastle (1976).

In patients suffering from vocal disturbances phonation may be affected in various ways: by alterations of the structure of the vocal folds and the superficial layer of epithelium, by disturbances of the innervation of some of the laryngeal muscles, or by wrong use of the larynx.

The connection between pathological changes of the vocal folds, the totally or partly modulated flow of air resulting in a pulsating air stream coming from the lungs, and the ultimately resulting vocal sound have been studied by Isshiki, Yanagihara, and Morimoto (1966), Yanagihara (1967a, b), Isshiki, Okamura, Tanabe et al. (1969). Their theoretical and experimental investigations proved the existence of a close relation between segmentation of the air flow and the ensuing glottal pulses with respect to the ultimately produced sound.

In some patients this not only appears in the open quotient, but also in the presence of a non-modulated part of the air flow via the glottis, the so-called wild air. The amount of air wasted per time-unit not only costs more energy, but the air stream is also inclined to turbulence, which may be perceived as breathiness.

The air flow rate seems to be an indicator for the functioning of the larynx and as such has been suggested as a diagnostic measure in studying laryngeal disturbances by Isshiki and von Leden (1964). A low flow may mean that the open quotient is small, only little air being allowed to pass per vibration cycle. A small open quotient indicates the presence of sharp glottal pulses, which means more upper partials in the source sound. However, if a low flow can be achieved only by an adjustment of the larynx with a condition of high muscular tension, this may lead to an unfavourable and less efficient result.

Such an adjustment of the larynx requires a high subglottic pressure in order to induce laryngeal vibration.

This shows that alone studying the consumption of air in phonation is not sufficient, but that evaluation of subglottic pressure during phonation must be included.

Energy for phonation is supplied by elastic energy stored in the thoracic wall after inspiration and by the expiratory muscles (Mead, Bouhuys, and Proctor, 1968).

The aerodynamic energy provided can be calculated fairly accurately from the product of the values of mean air flow rate and mean subglottic pressure.

The efficiency of voice production is determined by relating the produced sound power to the aerodynamic power provided, the so-called subglottic power.

Van den Berg (1956) studied for the first time the efficiency of voice production in a subject without laryngeal disturbances at various sound intensities and pitches.

Later experimenters have determined vocal efficiency in eight normal subjects and one patient only.

Aim of this study

The main object of this study is to establish the degree to which the efficiency of phonation in various vocal patients had been changed by their disorder.

Moreover, we intended to study whether the measuring of aerodynamic parameters possibly could be a clinically valuable diagnostic measure in cases of vocal disturbances.

In order to obtain reference data, measurements had to be performed in a group of normal subjects without vocal disturbances.

The therapeutic results in patients with vocal disturbances, classified in various categories, was to be objectivized by establishing the efficiency before and after treatment.

In Chapter 2, we present the experimental methods and the procedure for measuring the sound intensity, the air flow rate, and the subglottic pressure and for calculating the efficiency at various pitches in the vocal compass (phonetogram). In our research, the subglottic pressure has been measured with an indirect method, which has been verified by a direct method.

In Chapter 3, the analysis and evaluation of the obtained data are discussed. For every measuring series regression lines have been calculated, indicating the relation of sound intensity to air flow rate, subglottic pressure, or efficiency.

In Chapter 4, the results obtained in 63 subjects come up for discussion and reference values are established. Repeated measurements on the same normal subject enable us to arrive at a judgement of reproducibility and intra-individual dispersion of experimental data.

In Chapter 5, the results obtained in 64 patients are discussed.

The results of investigations of phonations in trained singers are discussed in Chapter 6. Aerodynamic and qualitative aspects and the efficiency of phonation are compared with those of non-trained voices.

In Chapter 7, a summary is given.

Chapter 2 Experimental methods

2.1 Introduction

In order to assess the efficiency of phonation, the subglottally supplied power has to be brought into relation with the produced vocal power.

We established the vocal power by measuring the intensity of the sound at a certain distance from the sound source.

The subglottally supplied power is equal to the product of the air flow rate q and the subglottic pressure p.

It would be important in this respect to know the exact relationship between the variations of the air flow rate and the variations of the subglottic pressure during a single cycle of vibration. Unfortunately, we cannot establish such a relationship. Therefore we had to be content to use the product of the mean flow rate and the mean subglottic pressure, which indeed are measurable. This approach is permitted, because of a rather low modulation depth of the subglottic pressure during phonation. Therefore $p \approx \bar{p}$ (van den Berg, Zantema, and Doornenbal, 1957; Kitzing and Löfqvist, 1975). In Formula 2-1

$$\int_{t}^{t+1} p \times dV \approx \bar{p} \times \int_{t}^{t+1} dV = \bar{p} \times \bar{q} \qquad (2\text{-}1)$$

A survey of our measuring equipment is given with the aid of Figure 2-1. Various parts are explained in more detail later on.

The subject is sitting on a chair, the flowhead and mouthpiece are situated in such a way that an unrestrained posture of neck and larynx can be maintained.

The subject breathes and phonates via a flowhead, with a mouthpiece which is kept between the teeth, a nose clamp preventing the passage of air via the nose.

The mouthpiece is chosen to prevent the variations of intensity resulting from changes in the size of the mouth opening. All phonations were made while keeping the vocal tract in the position for the formation of the vowel [ə] (*a*head).

The subject is asked not to cough into the flowhead in order to prevent mucous or saliva from getting onto the gauze of the flowhead.

Because swallowing of saliva with a mouthpiece between the teeth appeared to be difficult, there is the possibility of saliva running into the flowhead. In order to prevent this a perspex connecting

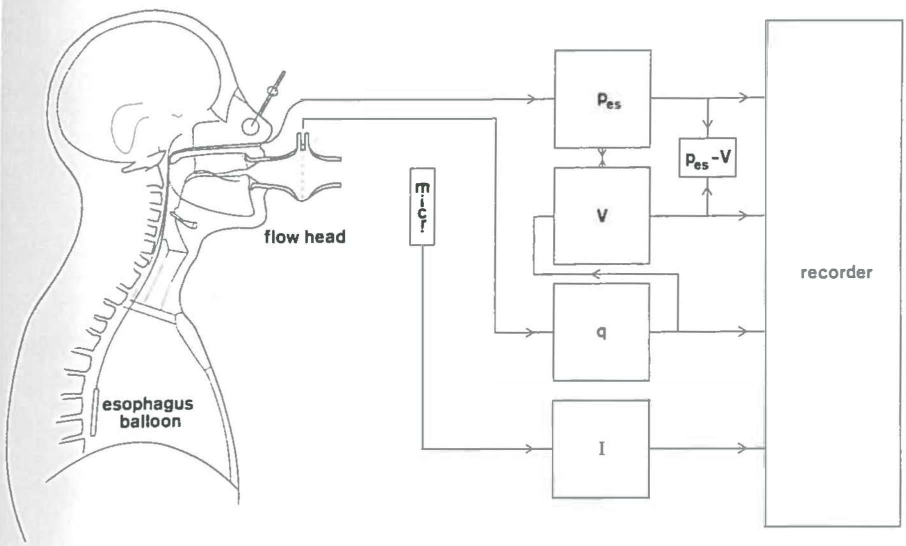


Figure 2-1. Schematic depiction of the experimental set up for the simultaneous measurement of sound intensity I, air flow rate q, variation of lung volume V, and oesophageal pressure p_{es}, together with apparatus for registering p_{es}-V diagrams.

piece with receptacle is inserted between mouthpiece and flowhead, see Figure 2-3.

The flowhead is connected with a pneumotachograph and a recorder.

The subglottic pressure was ascertained indirectly by measuring the pressure in the oesophagus. This indirect method necessitates the determination of the volumes of inspired and expired air. The value of these volumes may be obtained by analogue electronic integration of the air flow rate. For continuous integration of the air flow rate a modification of the pneumotachograph was necessary, and additional apparatus for the registration of p_{es}(oesophagus) - V(lung) diagrams was required.

The pressure in the oesophagus is related to the pulmonary volume (Buytendijk, 1949; Fry, Stead, Ebert et al, 1952). An automatic correction of the measured pressure in the oesophagus with respect to the momentary pulmonary volume was effectuated.

The sound intensity was measured

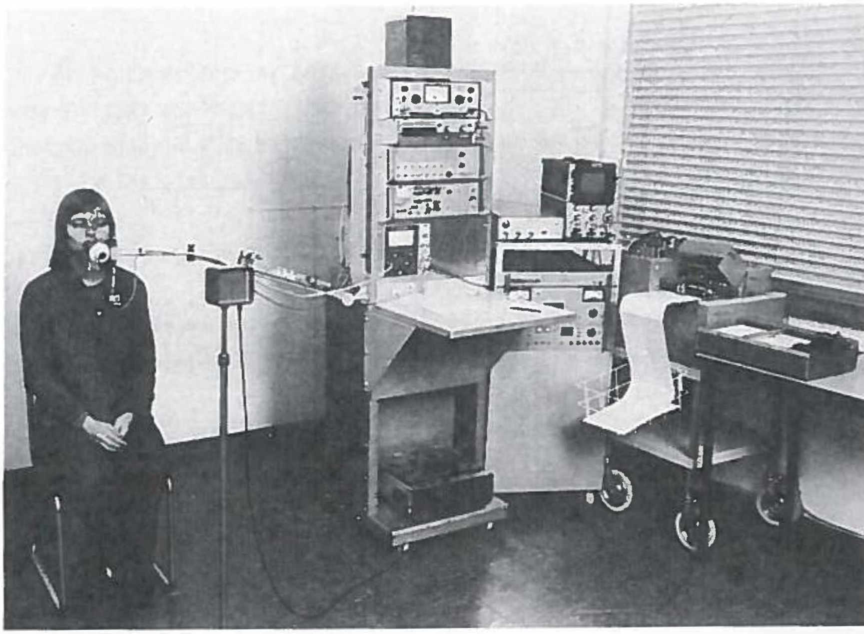


Figure 2-2A. The experimental set up.

with the aid of a microphone at a distance of 15 cm from the outlet of the flowhead.

The efficiency was established at various pitches[1]) and intensities.

The target pitch and intensity the subjects had to produce in phonation were indicated by additional apparatus. The produced sounds were registered and analysed by accessory apparatus.

The Figures 2-2 and 2-3 provide a survey of the complete measuring equipment.

2.2 Pitch and intensity of phonation

During the investigation the subject was asked to phonate at various pitches and intensities. The target pitch was indicated but not always produced. The range of pitches and intensities evidently depended on the vocal potential-

[1]) The terminology "pitch" is used in this monograph as a synonym of fundamental frequency.

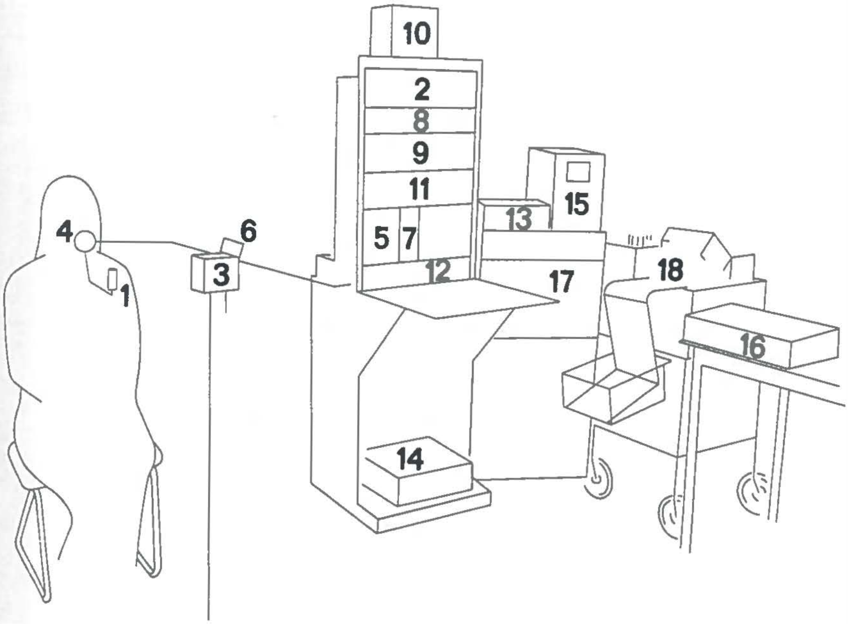


Figure 2-2B. The experimental set up:--
1. Microphone (Brūel and Kjaer); 2. Microphone amplifier (Brūel and Kjaer); 3. Sound intensity indicator for the subject; 4. Lilly Flowhead (Mercury Electronics); 5. Pneumotachograph (Godart); 6. Pressure transducer (Hewlett-Packard); 7. Carrier amplifier (Hewlett-Packard); 8. Frequency counter (Schneider); 9. Pitch Prompter (Groningen University Laboratory for Medical Physics); 10. Loudspeaker; 11. Precision rectifier with logarithmic convertor for the registration of sound intensity on the recorder, with built-in adjustable attenuator for the sound intensity indicator (Laboratory for Medical Physics); 12. Drift indicator for the Pneumotachograph, and amplifier for the expiration flow correction (Laboratory for Medical Physics); 13. Apparatus for automatic compliance correction (Laboratory for Medical Physics); 14. Tape recorder (Sony); 15. Oscilloscope (Hewlett-Packard); 16. X-Y recorder (Hewlett-Packard); 17. Ubiquitous Spectrum Analyzer (Federal Scientific Corporation); 18. Mingograph recorder (Elema-Schōnander).

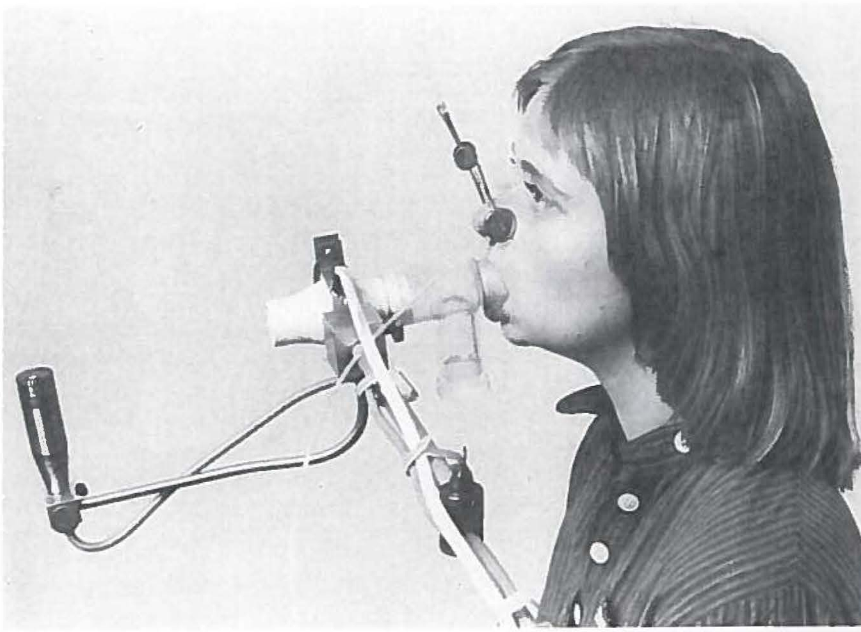


Figure 2-3. Detail of measuring set: microphone, flowhead, connecting piece with fluid receptacle.

ities of the subject or patient.

2.2.1 Choice of pitches and intensities of vocal sounds

2.2.1.1 Pitch Prompter

In order to indicate which pitch had to be produced the Groningen University Laboratory for Medical Physics (Dir.: Prof.Dr. Jw. van den Berg) constructed a Pitch Prompter according to our specifications.

This prompter consists of an oscillator with octave dividers for the frequency range relevant for the physiology of the voice. By installing four formant filters, adjusted to the formants of the vowel [ə], a sound could be obtained which was easy to intone by a subject. The sound is made audible via a loudspeaker. During phonation, the loudspeaker has to be disconnected in order to prevent interference with the sung sound. The examiner, however, is able to

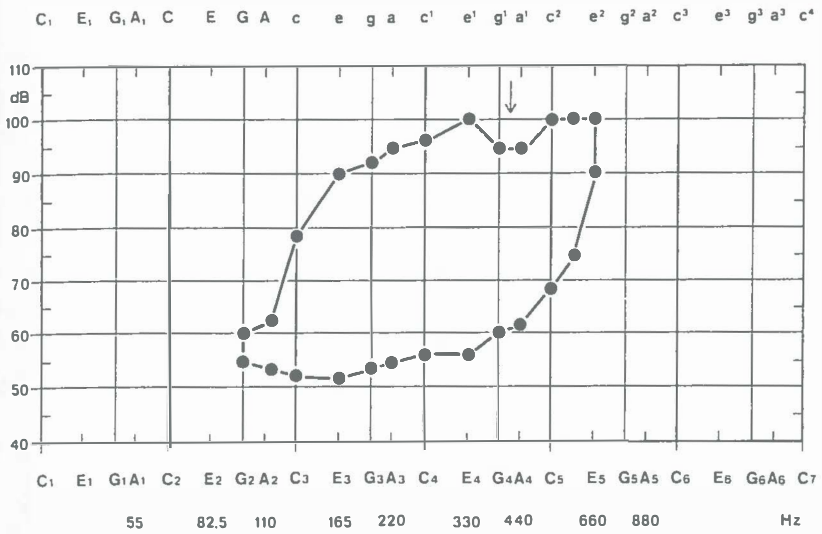


Figure 2-4. Phonetogram of an untrained male voice. The sound intensity has been represented in decibels (IEC-A) measured at a distance of 30 cm.. The arrow indicates the spot of the register transition in phonation at maximum intensity.

hear the tone via an earphone throughout the experiment.

A digital frequency meter (Schneider Electronique CF 350) is connected parallel to the loud-speaker, indicating the fundamental frequency of the prompt sound in herz.

[1]) The musical notations are taken from the American National Standard Terminology.

The range of the Pitch Prompter reaches from C2 (65 Hz) to C7 (2093 Hz)[1]). The adjustment for frequencies of the diatonic scale on C major is made possible by switches; there is a band-spread-fine-tuning adjustment in a limited frequency range possible. This possibility of varying the adjust-ment and reading off the frequency in herz from the frequency meter was mainly used in case a tone had not been sung according to the example. In such a case, the examiner is able to adjust the pitch prompter to the actually produced pitch (2.2.2).

2.2.1.2 Phonetogram

A phonetogram is a graphic representation of the vocal potentialities with respect to pitch and intensity (Calvet and Malhiac, 1952; Calvet, 1953; Luchsinger, 1953; Vogelsänger, 1954; Waar and Damsté, 1968; Schutte, 1975), see Figure 2-4.

The pitch is registered on the horizontal axis of the phonetogram. This axis is divided in octaves. The frequency span comprises the highest and the lowest frequency in which the vocal folds are able to vibrate.
On the vertical axis the sound intensity is registered.

For practical reasons the timbre of the voice is not mentioned in the discussion of the phonetogram. It is of course feasible to arrive at a system of registration, e.g. with a cipher-code, to indicate the quality of the voice in a certain area. It is very difficult though to reach agreement on a generally acceptable system.

In order to make a phonetogram, the subject is instructed to sing a tone at a pitch identical with the pitch from the prompter, at first as loud as possible and then as soft as possible. The subject must sing the same vowel each time. Minor variations of the vowel proved to have little influence on results. The making up of a phonetogram usually starts at C4 (262 Hz); then the dynamic compass is measured systematically till the highest frequency limit has been reached. After this the lower tones are measured until the lowest frequency limit.

The sound intensity is measured at a distance of 30 cm from the mouth with a microphone (Sennheiser MD 408N) and a sound intensity meter developed in the Groningen University Laboratory for Medical Physics. Reading off the result on this meter is made easier by using self-switching measuring ranges from 35 to 85 dB and from 75 to 125 dB. The complete set meets the conditions required for a frequency characteristic according to the IEC standard for curve A. The obtained measuring points are connected by straight lines.
A phonetogram can be made within 10 to 20 minutes.

Singing at a required pitch is certainly not easily effectuated

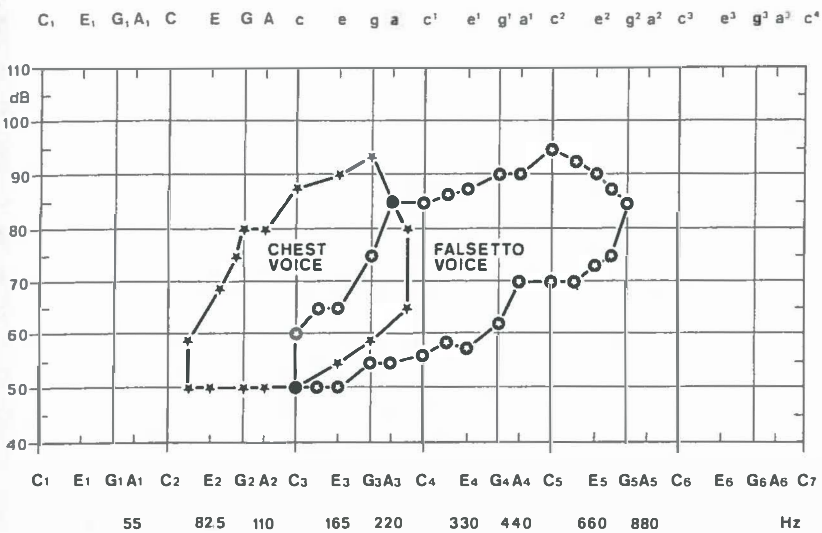


Figure 2-5. Phonetogram of the voice of a singer training as a countertenor because of the great range of his falsetto voice.

by all subjects. Many vocal patients appear not to be very musical and have little control over their voices. Moreover, the memory for tones has usually been poorly developed. In such cases the musical keenness of hearing of the examiner is of great importance. If a certain tone is not reproduced properly by the person, but at a pitch too high or too low, the examiner should be able to hear that. He may confine himself in such a case to registering the values of sound intensities at the actually produced pitches.

The phonetogram represented in Figure 2-4, taken from a subject without vocal training, shows in which pitches and with what dynamic potentialities this subject can phonate.

A decrease of dynamic potentialities may occur in a certain pitch area, especially in non-trained voices. This may be seen in Figure 2-4 at the region indicated by an arrow. This dip in the upper part of the phonetogram, as already described by Calvet and Malhiac (1952), is related to specific registers: for chest voice and falsetto voice, see Figure 2-5.

In this subject, who was given lessons as a countertenor because he was able to sing with a falsetto voice at an unusually low pitch, chest voice and falsetto voice could be distinguished on the basis of the timbre difference. In the octave below C4 the subject appeared to be able to phonate both in chest voice and in falsetto voice, though with limited vocal intensity in falsetto voice. For example, in falsetto voice he was not able to phonate louder than 75 dB at a pitch of G3.

The majority of the patients appeared to have vocal potentialities which did not extend to the falsetto voice. The use of the voice was mostly limited to one register only, which after Hollien (1972, 1974) may be indicated as "modal register": "it includes the range of fundamental frequencies that are normally used in speaking and singing".

2.2.1.3 Speaking voice pitch level

Because vocal disturbances in daily life occur mainly in speech rather than singing, it was considered of importance to determine also the average speaking voice pitch level. This was determined in three situations: --

a. during spontaneous conversation,
b. during counting from 1 to 20 at a fairly rapid pace,
c. in the recitation of a string of words (days of the week, months of the year),

as commonly practiced in phoniatric examination (Böhme, 1972, 1974; Pascher, 1975).

2.2.1.4 Pre-selected pitches

It was impossible to take measurements of the efficiency at many pitches in view of the required total time. In order to obtain comparable results we therefore made use of pre-selected pitches. Starting from an average speaking voice pitch of 110 Hz for the male voice and 220 Hz for the female voice, frequency steps of half an octave were taken. In Table 2-1 the series of pre-selected pitches is given which in an arbitrary sequence were investigated.

Some patients were unable to produce voice at these pitches.

If a distinct preference for a

Table 2-1. Pre-selected frequencies. The extreme frequencies within brackets were investigated if possible.

	E2	A2	E3	A3	E4	A4	E5	A5	
male voices :	(82.5),	110,	165 ,	220,	330,	(440)			Hz
female voices :			(165),	220,	330,	440 ,	660,	(880)	Hz

certain frequency appeared to exist we measured the efficiency at that frequency. These were cases, generally, of a person who appeared not to be able to vary sufficiently the pitch or was unable to sing the required tone. In such instances we had to accept the preferred frequency. It could be assumed that these persons phonated in their modal register.

The use of pre-selected pitches clearly had some drawbacks.

The subject in Figure 2-4 had an average speaking voice pitch at about C3 (123 Hz). At A2 (110 Hz) only very limited dynamic potentialities could be observed. This frequency already was close to the lower limit of his frequency span, so that investigation at 123 Hz provided a much better impression of the dynamic potentialities of the voice in daily use than at 110 Hz.

With the pre-selected pitches, difficulties due to coupling problems may be observed as a result of resonance (van den Berg, 1954). These problems occurred sometimes in well-trained subjects at about 330 Hz, but could be circumvented by using a slightly different frequency.

2.2.2 Pitch of the produced vocal sounds

During every measuring series the produced tones were recorded on tape in order to enable pitch evaluation afterwards.

For this purpose we used a tape recorder (Sony TC 105) with Automatic Volume Control, giving identical intensities in all phonations, which proved to be an advantage, when listening to the tape. With the AVC distortion was noticeable only in very loud phonations where the input preamplifier was overloaded.

The possibility of verifying the actual sung pitch retrospectively is of great importance. Trained subjects had no difficulty in singing the prompted tone. With non-trained persons and patients the results were sometimes very surprising, especially at first attempts. Sometimes subjects appeared not to be able to sing a tone at all at the required frequency.

Moreover, octave and even quint mistakes often occurred, i.e. the tone was an octave or a quint different from the given prompt tone. In octave mistakes, the sung tone of course often coincided with another of the string of pre-selected frequencies.

It also appeared that the task of maintaining the tone for a certain duration at a constant intensity itself already demanded much concentration. Since frequency changes produced only slight changes in dynamic output, we stressed the demand for a constant sound intensity in relevant cases. Afterwards we then measured the actual sung pitch.

2.2.2.1 Determination of pitch by auditory evaluation

The possibility of determining the pitch by auditory evaluation by matching the pitch of the Pitch Prompter heard through earphones with the actual sung pitch during phonation appeared to be reliable.

Establishing the pitch during phonation demands some musical skill and experience in comparing pitches, because phonation does not last very long. After phonation a comparison may be made between the remembered sung pitch and the varying prompter tone, in the course of which the memory image, however, is rapidly effaced by the continual hearing of the "seeking" prompter tone. In using a tape recorder the actual sung tone may eventually be repeated.

2.2.2.2 Instrumental determination of pitch

It is important to be informed on line about the actual sung pitch. Therefore we studied the possibilities of obtaining direct registration with the aid of available apparatus. Several devices were available: --

a. an electroglottograph according to Fabre,
b. a Froekjaer-Jensen pitchmeter,
c. a Melodyrecorder, and
d. a Frequencycounter with accessory filters.

All appeared to be very useful, provided the actual sung pitch remained within the selected measurement range of the apparatus. However, adjustment of the frequency range of the instruments proved to demand too much attention from the examiner during the test. Therefore we abandonned direct instrumental registration of pitch.

In a later stage of our study, we had the opportunity to use an Ubiquitous Spectrum Analyzer, Model UA-6B (Federal Scientific Corporation), which permitted determination of the fundamental frequency from the spectrum on an oscilloscope screen. The analyser was adapted in such a way that the vocal sound was analysed from 0-500 Hz with a nominal frequency resolution of 1 Hz, or for pitches from 0-1000 Hz, with a nominal frequency resolution of 2 Hz.

The analyser is equipped with a hold circuit, which is activated during phonation; after the phonation the "pointer" on the oscilloscope screen may be put above the fundamental frequency, in order to assess the frequency.

Taking into account that the tone that has been sung never is quite steady, we rounded off on a multiple of 5 Hz. If the apparatus was not available during a live measuring series, frequencies were later determined with it from the recorded tape.

2.2.3 Quality of produced vocal sound

Nearly all tape-recordings were checked afterwards by trained speech therapists, who judged the quality of the phonation. A phonation was judged as normal if it did not sound hoarse or breathy, or contain some other deviating quality.

2.3 Measuring of sound intensity, total sound power

2.3.1 Sound intensity

The sound intensity was measured at a distance of 15 cm from the outlet of the flowhead. A condensor microphone (Brüel and Kjaer 4145, cathode follower 2615) connected to a measuring amplifier (Brüel and Kjaer 2606) was used.

The frequency characteristic was adjusted to the conditions specified for IEC standard curve B.

In nearly all cases the weakest phonation appeared to rise above a level of 60 dB (SPL). This was well above the noise of the background, which varied from 40 to 45 dB.

For graphic recording of sound intensity in dB on the Mingograph recorder the Groningen University Laboratory for Medical Physics developed a precision rectifier with a built-in logarithmic converter. The smoothing filter of this converter has an integration time of 15 ms.

With the aid of a "window-discriminator" arrangement before the rectifier we ensured that an adaptable constant output signal would be provided if the signal fell outside the linear part of the dynamic range of the rectifier. The lower limit level of the "window-discriminator" was usually adjusted at 60 dB, the linear part of the dynamic range was 55 dB.

The output of the converter is also connected with a panelmeter via an adaptable attenuator. This meter is placed directly in front of the person and acts as indicator of sound intensity. With the aid of the attenuator the sensitivity of the meter can be adjusted to assure that the required intensity of sound will be reached when the needle of the meter is in the middle of the scale.

The apparatus was calibrated in decibel with a pistonphone (Brüel and Kjaer 4220) in accordance with the prescribed procedure. The deviations were smaller than ± 0.2 dB. The frequency characteristic was checked with a Beat Frequency Oscillator (Brüel and Kjaer 1022) and a Level Recorder (Brüel and Kjaer 2305) and met the requirements of the IEC standard for curve B.

Before every measurement the adjustment of the apparatus was verified by making use of a built-in reference signal in the measuring amplifier. By varying the input section of the measuring amplifier in steps of 10 dB linear control of the whole set-up for sound intensity registration was possible.

The influence of the room acoustics (eventual resonances), was examined by comparing the frequency dependent transmission characteristic in an anechoic room to that in the examination room. An Artificial Mouth (Brüel and Kjaer 4219) was used as sound source. The measuring microphone was set at 15 cm, 30 cm respectively 100 cm from the sound source. For the important frequency range of 100 Hz to 4000 Hz these characteristics were identical, apart from additional noise in the examining room. The differences due to the distances were taken into account (6 dB for 15 → 30 cm and 10 dB for 30 → 100 cm).

From this follows that the intensity measured at a distance of 15 cm is representative. The ambient noise spectrum fluctuations in the examining room were less than ± 1.5 dB and therefore could be neglected.

2.3.2 Total sound power

In order to calculate the total sound power we started from a known approach (van den Berg, 1956). We assumed that the sound intensity is constant on the surface of a hemisphere in front of the flow-head's outlet. The centre of this sphere lies in the centre of the outlet of the flowhead. We assumed that the sound energy on the other half of the sphere could be neglected.

The total sound power then amounts to $2\pi r^2 I$, in which r is the radius of the sphere (in our case 15 cm) and I the intensity of sound measured at this distance in front of the outlet. I is measured in dB SPL, i.e. the standard value in the equation for the intensity amounts to $10^{-12} W/m^2$.

2.4 Measuring of air flow rate (flow)

In our experiments the air flow rate was measured with a Pneumotachograph (Godart model 17212), Figure 2-6, which had been modified according to our specifications.

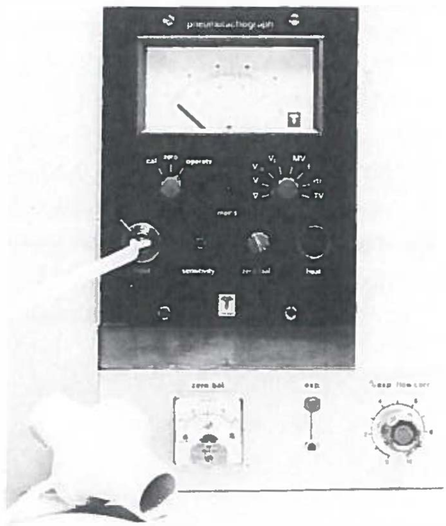


Figure 2-6.
Godart Pneumotachograph with Lilly flowhead. Eventual drift is indicated on the small meter below (1). With the potentiometer (2), the proper expiration flow correction factor may be adjusted to prevent the volume curve from drifting.

2.4.1 Description of the pneumotachograph

A flowhead (flow-pressure transducer) acts on the principle that a resistance in the respiratory tract gives rise to a pressure difference

$$p = q \times R \qquad (2\text{-}2)$$

in which p is the differential pressure over the flowhead, q the air flow rate and R the resistance. The pressure is linear proportional to the air flow rate if the resistance is constant. This is the case if in a gas of constant composition and temperature the flow has a laminar character. The construction of flowheads aims at achieving this condition for a certain range of air flow rates.

We evaluated two different types of flowheads: the Fleisch flowhead, consisting of a number of parallel connected cylindric tubes (Fleisch, 1925, 1956) and the Lilly flowhead with a fine-meshed gauze (Lilly, 1950). For the Fleisch flowhead at laminar flow the following formula is applicable

$$R = \eta \times \frac{8l}{n\pi r^4} \qquad (2\text{-}3)$$

In this equation η is the viscosity of the gas, l is the length of the cylinders, r their radius and n their number.

We experienced a number of difficulties in practical use because η is not a simple quantity. For ideal gases, i.e. gases in which the molecules may be considered as very small elastic globules, not excercising field forces on each other, Maxwell derived that η is proportional to $\sqrt{T}$ and independent of pressure; T is the absolute temperature. In a mixture of ideal gases the viscosity of the mixture equals the weighted sum of the viscosities of the composing gases. In practical use this calculation requires correction (Kestin, 1963). However, in view of an analysis of the influence of main factors, the weighted sum can be used as a first approximation for calculating the viscosity of a gas mixture.

2.4.1.1 Choice of the flowhead

In the standard model the Pneumotachograph is delivered with a Fleisch flowhead. This flowhead is composed of metal tubes and has to be heated in order to prevent condensation of aqueous vapour in the expired air. The regulating effect of the heating system appeared to influence the pressure difference and therefore the air flow rate derived from it.

In administering dry air at a constant flow rate and temperature the measured variations in the air flow rate appeared to be about 2.5%. The variations are approximately independent of the mean flow rate.

The temperature of the air leaving the flowhead was measured by an electronic thermometer and appeared to vary between 34.5 ^{o}C and 42 ^{o}C, i.e. the variations amounted to about $\pm$ 4 ^{o}C.

The effect on the flow measurement has to be explained by the influence of the temperature on the viscosity and the volume variations going along with temperature variations.

In the mentioned temperature range the temperature coefficient of η for air is about 0.2%/^{o}C. The viscosity then changes about $\pm$ 4 x 0.2% = $\pm$ 0.8% and the volume variations at constant pressure amount to $\pm$ 4 x 0.37% = $\pm$ 1.5%. Taken together, this means variations of $\pm$ 2.3%, i.e. variations of the same size as the measured ones. These variations are permissible if only the air flow rate is of importance, but with integration of this quantity over a fairly long time their effect proved to be considerable.

In order to avoid this disadvantage we used a flowhead according to Lilly. This flowhead has a cover of synthetic material and a fine-meshed metal gauze, both with a small heat capacity. Therefore condensation of moisture from expired air does not occur, which makes heating of this flowhead superfluous. An additional advantage is that the subject may inspire air at room temperature.

2.4.1.2 Linearity of the pneumotachograph

The linearity of the pneumotachograph system including electronics was tested by applying known pressures, measured with an oblique tube manometer, at the input of the apparatus. The pneumotachograph appeared to be linear up to an output signal of 9 Volt, respectively -9 Volt. The sensitivity could be adjusted between about 40 Pa (4 mmH_2O) and about 80 Pa (8 mmH_2O) for an output voltage of 5 Volt.

We used a Lilly flowhead (Mercury Electronics Ltd, Glasgow), with a typical pressure difference for room air of normal temperature of 24 Pa (2.4 mmH_2O) for 1 l/s. The flowhead was used with the pneumotachograph for an output voltage of 5 Volt at 2 l/s.

For the purpose of calibration we used a Godart Calibration set in series with the Lilly flowhead. The calibration set consists of a number of tubes with a calibrated opening. With the aid of a pump an adjustable air flow can be conducted through these tubes. The pressure differences are measured at the calibrated opening by an oblique tube manometer belonging to the calibration set. For this calibration room air was used.

The results of the measurements are represented in Figure 2-7. Within the random measuring error the complete set up appeared to be linear in both directions up to an air flow rate of 2 l/s.

The proportionality factor of the flowhead we used appeared to amount to 32.5 Pa.s/l (3.25 mmH_2O.s/l).

2.4.1.3 Response time of the pneumotachograph

The response time of the differential pressure transducer has been stated by the manufacturer to be smaller than 15 ms. From the registrations it appeared that the use of the Lilly flowhead, connected to the pneumotachograph by flexible tubes (length 190 cm, inner diameter 3 mm), influenced the reaction speed of the system very little only.

The separate pulses of air caused by opening and closing the glottis during phonation could not be observed. The mean air flow rate was registered, meeting our purpose. During very low pitches an indication of the pulsating character of the air flow could be observed.

2.4.2 Properties of gases passing the flowhead and their influence on flow measurement

In testing the pneumotachograph, room air was used. During phonation, room air is inspired, but the expired gas has a different composition and temperature. This influences the factors q and R in the Equation for the differential pressure (2-2), as is known from the literature on pulmonary function and anaesthesiology (Lilly, 1950; Silverman and Whittenberger, 1950; Bartels, Bücherl, Hertz et al., 1959; Greer, 1964, 1966; Grenvik and Hedstrand, 1966; Grenvik, Hedstrand, and Sjögren, 1966; Herzog, 1970; Osborn, Beaumont, Raison et al., 1968;

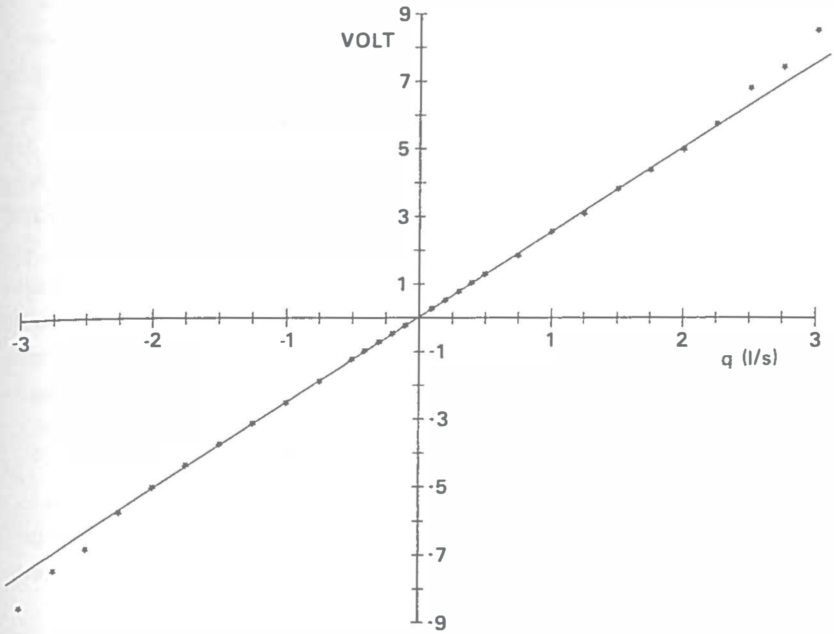


Figure 2-7. Linearity of the Lilly flowhead. On the X-axis, the air flow rate, adjusted with the Godart Calibration Set, is depicted in liter/s; on the Y-axis, the output voltage of the Godart Pneumotachograph is given. The sensitivity of the Pneumotachograph has been adjusted in such a way that an air flow rate of 500 ml/s provides an output voltage of 1.25 V.

Egan, 1969; Fletcher, 1969; Osborn, Elliott, Segger et al., 1969; Blumenfeld, Turney, and Cowley, 1973; Turney and Blumenfeld, 1973; Blumenfeld, Wilson, and Turney, 1974).

Data concerning inspired and expired air and their composition can be found in the literature (Otis, 1965; Diem and Lentner, 1968), see Table 2-2. It was assumed that the inspired air is 50% saturated with water vapour. The differences, with respect to the percentages of CO_2 and water vapour, are considerable.

2.4.2.1 Difference in viscosity of inspired and expired air

Table 2-2. Gas composition of respiratory air in percentages, at a pressure of 101 kPa (760 mmHg). For inspired air, a relative humidity of 50% at 22 ^{o}C was assumed. Expired air was considered to be 100% saturated with water vapour and to have a temperature of 37 ^{o}C.

	F_{N_2}	F_{O_2}	F_{CO_2}	F_{H_2O}
Inspired air	77.99	20.68	0.03	1.3
Expired air	74.87	15.23	3.65	6.25

From handbooks (Hirschfelder, Curtiss, and Bird, 1954; Lange, 1967; Weast, 1968) the viscosity of various gases may be derived, Table 2-3.

Assuming that the viscosity of mixtures of gases in a first approximation equals the weigthed sum of the viscosities of the composing gases, the viscosity of the inspired air at 22 ^{o}C (η_{22}), respectively of the expired air at 37 ^{o}C (η_{37}) may be estimated as follows

η_{22} = 18.17 μPa.s

η_{37} = 18.38 μPa.s

Despite the relatively great differences between inspired and expired air the difference in viscosity only amounts to 1.13%. The addition to the mixture of carbondioxyde gas and water vapour with a low viscosity and the withdrawal of oxygen with a comparatively high coefficient, almost totally compensates for the increase in the viscosity caused by the rise in temperature.

From this calculation follows that the resistance R in Equation (2-3) is 1.13% larger for expired air than for inspired air.

2.4.2.2 Difference of volume of inspired and expired air

The volume of the inspired air is different from the volume of the expired air because of differences in temperature and composition. The total pressure is supposed to be 101 kPa (760 mmHg). The changes of volume in consequence of altered composition and temperature may be calculated by assuming that the amount of nitrogen always remains the same. Nitrogen indeed is warmed up in inspiration but the total amount of nitrogen in the expired mixture of gases is the same as in the inspired air. The alteration due to the change in the composition may be derived from the size of the fractions (Table 2-2). The alterations due to the change of temperature may be derived from the values of the absolute temperature (gas-laws). If a volume V_1 containing 77.99% N_2 and a temperature of 22 ^oC (295 K) is inspired and a volume V_2 containing 74.87% N_2 and a temperature of 37 ^oC (310 K) is expired, then

$$V_2 = V_1 \times \frac{77.99}{74.87} \times \frac{310}{295}$$

$$= V_1 \times 1.0952 \qquad (2\text{-}4)$$

In breathing via the flowhead, integration of the flow signal during a steady state will yield a larger volume during expiration than during inspiration. In this instance the effect of the viscosity acts in conjunction with the effect of the volume according to the above mentioned calculation, causing a total increase of about 11%. However, due to the presence of a comparatively extensive dead space, not all of the expired air may be considered to be heated inspired air.

The physiological dead space is about 150 ml, moreover there is the additional volume of the flowhead and the perspex connection of flowhead and mouthpiece. The total dead space therefore amounts to about 275 ml. The influence of a dead space of such an extension is not negligible, because per respiration cycle a minimum of 350 ml is necessary in order to provide the physiologically required refreshing of the air in the lungs. Altogether, this practically will cause the difference to be less than 11%, moreover, the difference will be still less because the expired air is already somewhat cooled off when arriving at the gauze.

Table 2-3.
Viscosities of the air-constituent gases, in micropascalseconds.

	22 ^oC	37 ^oC
N_2	17.7	18.5
O_2	20.3	21.3
CO_2	15.4	16.1
H_2O	9.9	10.5

2.4.3 Adjustment of the pneumotachograph

Because it was intended to measure the air flow rate in phonation, i.e. the flow rate of the expired air, the instrument was calibrated by means of a gas mixture with properties nearly identical to those of expired air, namely room air heated to a temperature of 37 °C and saturated with water vapour to 100%. The computed viscosity of this humid calibration mixture is 1% higher than that of expired air, due to the lack of CO_2 and the somewhat different proportions of N_2 and O_2. For the adjustment of the pneumotachograph previous to each measuring series and for checking calibration constancy after the series dry calibration air from a cylinder was used.

The air flow rate was regulated with a precision needle valve and measured with a Brook Sho-Rate Flowmeter '250' model 2-1357-8605 for the range from 80-1200 ml/s (metering tube R6-25-A with Tantalum Float). The viscosity of this dry calibration air at 22 °C lies nearly in the middle between the viscosity of the inspired air at 22 °C and that of the expired air at 37 °C and, therefore, is 1.5% smaller than the calculated viscosity of the mentioned humid calibration mixture.

The correct adjustment and the check after the measurements always took place with the same flow rate of dry cylinder air. This flow rate caused a pressure difference equal to that at the flow rate of 500 ml/s of the humid calibration mixture.

2.5 Measuring of variations in pulmonary volume

By time integration of the air flow rate the changes of the lung volume can be determined. This is important because there is a certain relationship between lung volume and intra-oesophageal pressure.

For the integration we made use of a modification of the electronic integrator, which is part of the Godart Pneumotachograph, see Figure 2-8.

The expiration flow signal, after having been separated from the inspiration flow signal, was conducted further via an externally adjustable amplifier; the inspiration flow signal was transferred unaltered. The amplitude of the transferred expiration flow signal could be adjusted between 90% and 100% of the detected value. This appeared to be of great value in the continual registration of the volume curve, as drift could be corrected for. (This electronic option was not available in the standard model of the pneumo-

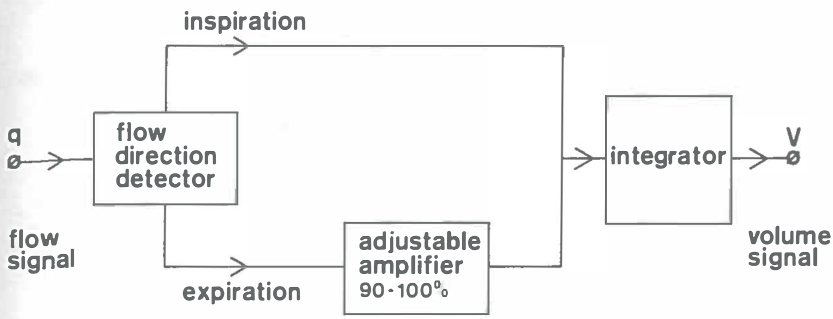


Figure 2-8. Diagram of the set up for the expiration flow correction method used in this investigation. The expiration flow signal can be attenuated continuously to maximally 10%.

tachograph, but was added by the manufacturer to the apparatus, following our specifications.)

After passing the expiration flow correction amplifier the signal was again combined with the inspiration flow signal and fed to the volume integrator.

The total value for the volume integration is limited so that if a certain output voltage is reached (positive or negative) automatic resetting of the integrator to 0 V ($\pm \geq$50 mV) will follow.

The total range of the integrator comprised 4.4 liter. Therefore the volume of the lungs during quiet breathing could be registered without resetting, as well as the inspiration before phonation and the expiration during phonation.

2.5.1 Calibration of flow and volume measurement

In 2.4.3 has already been mentioned that in calibration of the pneumotachograph we started with air of 37 ^{o}C, 100% saturated with water vapour. For practical purposes the flow calibration was performed simultaneously with the calibration of the volume integrator, by letting an exactly known volume of air (2 liters) of 37 ^{o}C, 100% saturated with water vapour escape by means of a displacement method via the flowhead. At a setting of 100% for the expiration signal the sensitivity of the common flow amplifier was adjusted in such a way that the volume indicator registered 2 liters. At this adjustment air from a high pressure cylinder was conducted through the flowhead via the Brooks flowmeter. The air flow rate was varied in order to obtain in 4 seconds a volume indication of 2 liters. The reading of the Brooks flowmeter then corresponds with an air flow rate of 500 ml/s of air at 37 ^{o}C and a 100% saturation with aqueous vapour. This reading was used for later calibration.

2.5.2 Registration of volume curve

The registration of a volume curve may show deviations which may lead to erroneous interpretations of the relation between lung volume and oesophageal pressure. The most important source of error in this respect lies in the use of the flowhead, as discussed in 2.4.1; moreover, an inaccurate zero adjustment of the flow amplifier may lead to faulty registrations.

2.5.2.1 Course of volume curve due to drift in flow amplifier and/or integrator

With zero flow, e.g. in case of a disconnected flowhead, the amplifier output and therefore the input of the integrator ought to show a mean voltage of 0 V. In such a case the output signal of the integrator should be constant.

As a result of fluctuations of temperature etc., it may occur that at zero flow the input voltage of the integrator is not zero, introducing a drift in the integrator. Because minimal drift is of importance in view of the accuracy with which the subglottic pressure can be measured, a standard has been established for the adjustment of the flow amplifier.

Measurements of drift of the pneumotachograph proved that adjustment of the flow amplifier at zero flow could be performed in such a way that the output did not show a greater deviation from zero than $\pm$ 1 mV, corresponding with $\pm$ 0.2 ml/s and an integrator drift smaller than 60 ml during a period of 10 minutes.

For practical purposes the Groningen University Laboratory for Medical Physics designed a drift indicator to facilitate the adjustment to limit the drift to less than 60 ml during a period of 10 minutes. The drift of the amplifier will cause no problem within the time needed for one

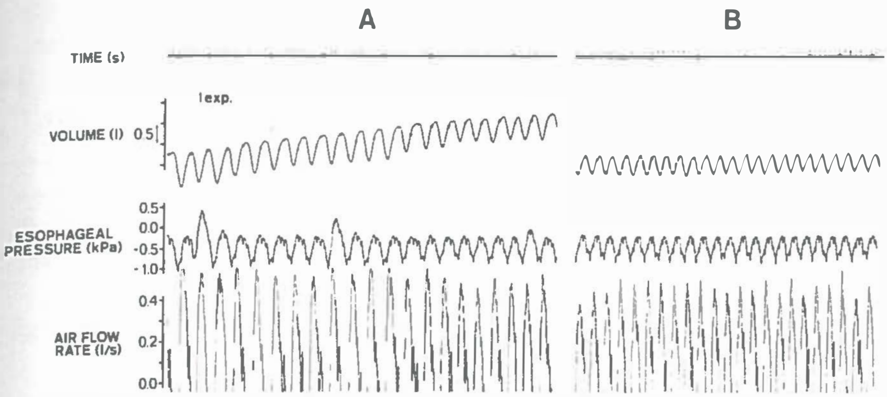


Figure 2-9. Volume curves from a quietly breathing subject, with representation of expiration flow, pressure variations in the oesophagus, and lung volume curves. Because in normal phonation the inspiration flow is of no importance, only the expiration air flow rates have been registered. In (A) the volume curve shows a drift in the direction of the expiration; in (B) the drift has been eliminated by a proper adjustment of the expiration flow correction.

measuring.

During the measuring series the presence of drift in the flow amplifier and/or integrator is checked regularly and corrected by adjustment if necessary.

2.5.2.2 Course of volume curve due to differences in physical properties and volumes of inspired and expired air

As a result of the differences mentioned in 2.4, in the standard model of the pneumotachograph, after integration of the flow signal during quiet breathing, a larger volume was found for expired air than for inspired air, see Figure 2-9.

Figure 2-9A shows a registration of the changes in oesophageal pressure during a period of quiet breathing.

Expiration air flow rate and volume curve have been registered simultaneously. After some time the course of the volume curve appeared to be displaced in the direction of the expiration. After some 9 breaths of 700-750 ml the total volume of the lungs seems to be diminished by 500 ml, i.e. about 7.5%. This result corresponded fairly well with the expected value (2.4.2.2).

By reducing the expiration flow signal by about 7.5% drift could be eliminated from the volume curve, see Figure 2-9B. (Mead and Whittenberger, 1953, arrived at similar correction data on the basis of experimental studies.)

The difference of the volumes during inspiration and expiration depends on the temperature and relative humidity of the inspired air at the moment of measuring. Previous to every measurement series the necessary correction factor was experimentally assessed. Therefore we checked by inspection of either the volume curve on the registration paper during quiet breathing or the spiral drifting of the p_{es}-V loops, see Figure 2-18, to make sure that drift no longer occurred. If the correction had been adjusted properly the loops of successive respirations were superimposed.

In considering this problem, we should remark that it is sometimes attempted to correct the drift of the volume curve by a bias of the flow amplifier. If this is done, then when the flowhead is disconnected, there will be a drift equal to that for which the respiration had been corrected, but in the opposite direction. We could not accept this method because when the breath is held there would be a drift. Therefore we opted for the discussed modification of the standard pneumotachograph.

2.6 Measuring of oesophageal pressure

To measure the oesophageal pressure we used an oesophagus balloon situated in the lower 2/3 part of the oesophagus.

The oesophagus balloon with catheter was inserted through the nose after the mucosa had been anaesthetised with oxybuprocaine HCl (Novesine^{R}).

The catheter was marked at a distance of 38 cm from the tip and inserted until the mark reached the nostril and then was fixed by adhesive plaster.

The catheter was connected with a pressure-transducer (Hewlett-Packard, 267 BC) with an amplifier (Hewlett-Packard, 8805B). The output signal of the measuring amplifier was transferred to the recorder.

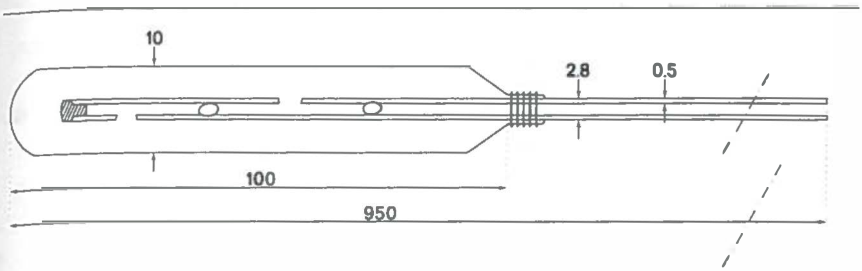


Figure 2-10. Oesophagus balloon catheter (sizes in mm).

2.6.1 Oesophagus balloon catheter

The oesophagus balloon catheter (Lode Instruments B.V., Groningen) is made of latex rubber, long 10 cm, diameter 1 cm, wall thickness smaller than 0.15 mm. The balloon is fastened to the end of a polyethylene catheter with an internal diameter of 1.8 mm, a length of 95 cm and a wall thickness of 0.5 mm. In the lower part of the wall of the catheter a number of holes have been made, which are enclosed by the balloon, see Figure 2-10.

The oesophagus balloon catheter is connected to a system with three cocks that also can be used as manifold connecting piece. With the aid of this system, the oesophagus balloon catheter is connected to: --

a) the pressure transducer,
b) an U-shaped water manometer, and
c) an air-filled syringe.

For a correct transfer of the pressure on the balloon via the catheter to the pressure transducer a certain volume of air has to be brought into the system.

An insufficient filling, causing the balloon to be sucked into the holes as well as a superfluous filling, which causes the balloon to be blown up, may induce faulty registration of the oesophageal pressure (Milic-Emili, Mead, Turner et al., 1964; Tostmann, Siegert, and Klingholz, 1979).

Experimental results proved that reliable data could be obtained with a filling of air of 3.5 ml. The function is controlled by observing the curves on the registration paper.

The nominal volume displacement coefficient of the transducer amounted to about 2.3 mm^3/MPa (0.03 mm^3/100 mmHg).

The changes of the balloon volume caused by the corresponding changes of pressure during phonation are negligible.

2.6.2 Linearity of the pressure measuring system

The pressure transducer is linear for a range from -13 kPa to +53 kPa (-100 mmHg to +400 mmHg).

The linearity of the total system was tested for the range from -5 kPa to +10kPa (-50 cmH_2O to +100 cmH_2O) by placing the balloon in a perspex cylinder in which the pressure outside the balloon could be varied. The result is represented in Figure 2-11. It appears that the pressure inside the balloon follows the outside pressure well in the pertinent range.

2.6.3 Response time of the pressure measuring system

The already mentioned perspex cylinder was also used to measure the response time of the pressure measuring system.

For this purpose, the bottom of the cylinder was replaced by a tight rubber membrane. At a raised pressure in the cylinder a sudden release - necessary for the step response - was induced by rupturing the rubber membrane. The pressure variations in this shock tube were measured with a rapid response pressure transducer and the balloon catheter manometer system. Both outputs were simultaneously registered on the Mingograph recorder with high paper speed.

From these registrations, the frequency response was computed by the method described by McDonald (1960), Vierhout (1963), Yanof, Rosen, McDonald et al. (1963), Yanof (1965), Bottaccini, Burton, and Lim (1967), and Wesseling and van Vollenhoven (1969).

A linear dynamic response up to 30 Hz was found. For registration of quiet breathing, 12 to 18 respirations per minute (0.2-0.3 Hz), a linear dynamical behaviour up to 4 Hz is considered to be sufficient (McCall, Hyatt, Noble et al., 1957). Therefore the measuring system works fast enough for registering the mean pressure in the oesophagus during phonation and the changes of pressure shortly after the onset or cessation of phonation.

2.6.4 Calibration of the pressure measuring system

The pressure measuring system was calibrated before every measuring series by connecting it

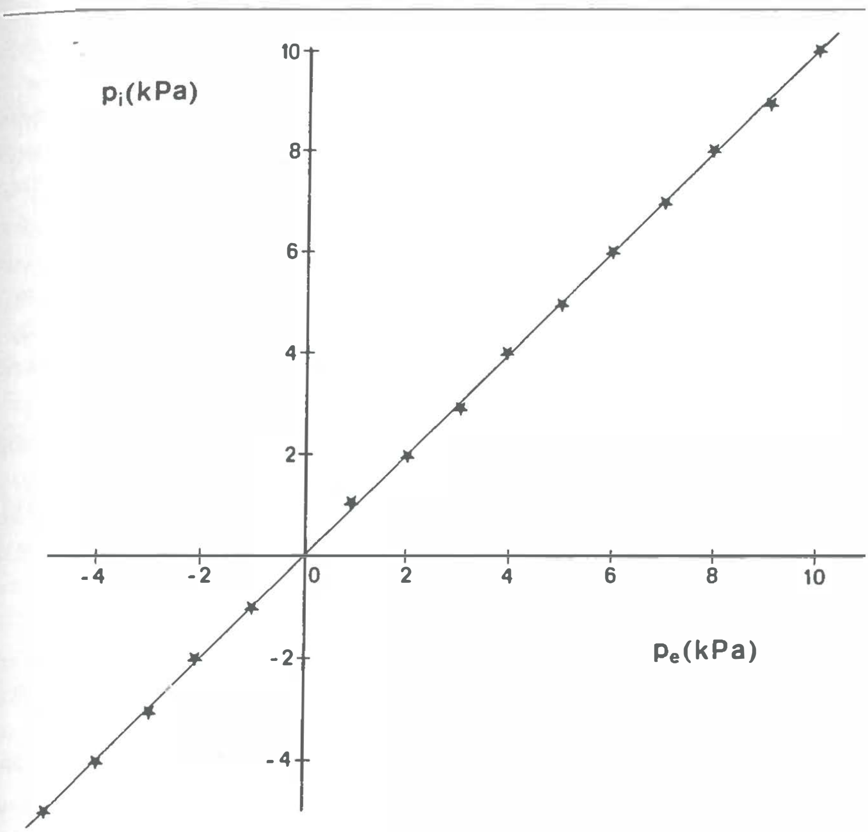


Figure 2-11. Calibration of the oesophagus balloon catheter manometer system with the aid of a pressure tank: pressure outside balloon, p_e, pressure inside balloon, p_i.

to the water manometer.

2.7 Determination of subglottic pressure

The subglottic pressure can be measured by direct or indirect methods. In a direct method the pressure is measured directly in the trachea. In the past, several routes have been taken for this purpose: --

a. Via a tracheostoma. Since the first measurements by Cagniard-Latour (1837) until about 1960 (Strenger, 1958), subglottic pressure values were obtained in this way (Roudet, 1900a, b;

Gutzmann and Loewy, 1920).

b. Via the larynx. Van den Berg (1956) used a catheter conducted through the nose and the glottis and brought into the subglottic space, to verify the results obtained by an indirect method described by him. Perkins and Koike (1969) and Kitzing and Löfqvist (1975) used in the same way a catheter-tip manometer for high-frequency registration of the subglottic pressure.

c. Via a hollow needle percutaneously inserted into the subglottic space. A considerable number of investigations, mainly american, yielded subglottic pressure values (Isshiki, 1959, 1961, 1964; Strenger, 1959; Ladefoged, 1960; Kunze, 1962, 1964; McGlone, 1963; Isshiki and von Leden, 1964; Yanagihara and von Leden, 1966; Rubin, LeCover, and Vennard, 1967; Lieberman, 1968; Perkins and Yanagihara, 1968; Loebell, 1969; McGlone and Shipp, 1971; Murry, 1971; Murry and Brown, 1971; Shipp and McGlone, 1971).

For obvious reasons the numbers of examined persons were small. The direct methods are not suited for routine clinical practice.

Van den Berg (1956) introduced an indirect method for measuring the subglottic pressure. In this method, the subglottic pressure is derived from changes in oesophageal pressure. During respiration and phonation the pressure in the oesophagus is measured. The oesophageal pressure is increased during phonation, and the subglottic pressure during phonation can be derived from this increase, but not without paying attention to other factors. The reason is that the pressure in the oesophagus depends on the lung mechanics, conditioned by certain mechanical properties of the lungs, as we have already seen from variations in oesophageal pressure during respiration, see Figure 2-9.

The method described by van den Berg has been used for phonetic research by Ladefoged, Draper, and Whitteridge (1958), Draper, Ladefoged, and Whitteridge (1959), Strenger (1959), Draper and Ladefoged (1960), Ladefoged (1960, 1962, 1963), and Ladefoged and McKinney (1963).

Kunze (1962, 1964) criticized this indirect method and considered it not usable for measuring the subglottic pressure.

He arrived at this conclusion on the basis of his comparative investigations with a direct method (punction of the tracheal space). We assume his subjects did not perform the tests properly.

The indirect method in its original version requires an abrupt phonation stop, the breath is held on with open glottis. This manoeuvre demands some training. Kunze measured in fact the subglottic pressure together with a pressure dependent on the lung volume.

Induced by the conclusions drawn by Kunze and their own erroneously interpreted curves, Rubin, LeCover, and Vennard (1967) also rejected the oesophageal balloon method.

Ladefoged (1964), Bouhuys, Proctor, and Mead (1966), Bouhuys, Mead, Proctor et al. (1968), Lieberman (1968), and Schwabe and Siegert (1973), did not agree with Kunze's conclusions and pointed out that the oesophageal balloon method is reliable indeed, provided that the lung volume is taken into account.

This indirect method was also used by Cavagna and Margaria (1965, 1968), and Cavagna and Camporesi (1974).

Siegert et al. (Siegert, 1969, 1971; Klingholz and Siegert, 1972; Siegert and Klingholz, 1973; Höfner and Siegert, 1975) used the indirect method at the onset of the voice. Therefore their results cannot be compared with our data.

Nishida and Suwoya (1964) described a so-called interruption method for indirect measuring the subglottic pressure. In this method, the air stream via a breathing mask is temporarily interrupted and the increase in pressure within the mask is measured.

Kittel and Moser (1976) used a body plethysmograph for determining the subglottic pressure in stutterers. They related the lung volume (obtained by integration of the electric signal from a pneumotachograph) and the intrathoracic pressure. The intrathoracic pressure is related to the subglottic pressure during phonation. The use of a body plethysmograph demands skilled personnel and much experience in interpreting the obtained curves.

In the following sections we will further discuss the calculations in detail.

2.7.1 Correction for mechanical properties of the lungs

The role of the mechanical properties of the lungs in calculating the subglottic pressure may be explained with the aid of the p_{es}-V diagram of the lungs, see

Figure 2-12. The p_{es}-V diagram plays an important role in lung function examination. For details we refer to relevant literature (Buytendijk, 1949; Mead, McIlroy, Selverstone et al., 1955; Donleben, 1959; Hilvering, 1963) and the "Handbook of Physiology" (1964) ed. by Fenn and Rahn. For a discussion in connection with voice production, we refer to the publiications of van den Berg (1956) and Bouhuys (1966).

During a complete respiratory cycle a loop is formed which in normal lungs resembles an ellips, see Figure 2-12A. In such a case the mechanical function of the lungs can be approached with a simple electric analogue, consisting of a condensor with a constant capacity C in series with a constant resistance R. The condensor represents the compliance of the lungs, the electrical resistance the viscous resistance, see Figure 2-12B.

For C, the compliance, applies:

$$C = \frac{\Delta V}{\Delta p_{es}} \qquad (2\text{-}5)$$

in which ΔV is the change in volume in a spirometer connected to the lungs (the change in the lung volume is then $-\Delta V$) and Δp_{es} is the corresponding change in the pressure in the oesophagus, as observed in very slow inspiration and expiration.

For normal lungs $C \simeq 2.5$ liter/kPa (0.25 liter/cmH_2O) (Buytendijk, 1949; Stead, Fry, and Ebert, 1952; Marshall, 1964; Spells, 1969).

The compliance is primarily responsible for the slope of the loop and can be calculated from it.

For R, the viscous resistance, Formula 2-6 applies:

$$R_{total} = R_{airways} + R_{tissues} \qquad (2\text{-}6)$$

$R_{tissues}$ is about 20% of R_{total} (Marshall and Dubois, 1956). The resistance of the upper airways, i.e. from the vocal folds to the lips, is about 25% of the total resistance (Ferris, Opie, and Mead, 1960; Hyatt and Wilcox, 1960; Schiratzky, 1964, 1965a, b).

The total resistance varies between 0.13-0.33 kPa.s/liter (1.3-3.3 cmH_2O.s/l), with a mean value of 0.23 kPa.s/l (2.3 cmH_2O.s/l) (McIllroy, Mead, Selverstone et al., 1955; Ferris, Mead, and Opie, 1964; Marshall, 1964; Fisher, Dubois, and Hyde, 1968; Spells, 1969).

The viscous resistance is responsible for the width of the loop and its value may be computed from it. When inspiration and expiration

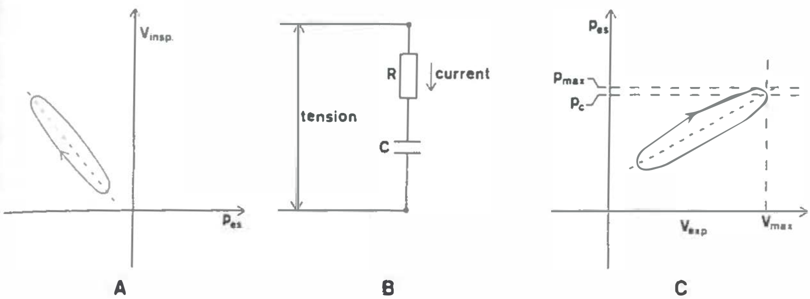


Figure 2-12. The p_{es}-V diagrams:

A. Schematic representation of the p_{es}-V diagram. At inspiration the oesophageal pressure becomes more negative (see also Figure 2-9).

B. Electric analogue model of the lungs, consisting of serial RC circuit with capacity C and resistance R. The capacitor represents the compliance of the lungs, the resistor the viscous resistance, and the tension (voltage) the effective lung pressure producing inspiration or expiration. As the input voltage varies, the current through the network varies out of phase with the voltage.

C. As a result of the phase shift, the maximum pressure p_{max} will be reached earlier than the maximum volume V_{max} and its corresponding pressure p_c. The volume V_{max} will be reached when the direction of the flow changes (i.e. when the air flow is zero). Practically, the difference between p_{max} and p_c is mostly small and depends on the magnitude of the viscous resistance and the respiratory frequency. In experiments p_c is used as reference pressure for the determination of the subglottic pressure, see 2.7.

are very slow, the corresponding changes of pressure can be neglected and the width of the loop is zero.

With sinusoidal pressure changes the extreme pressure values are reached somewhat earlier than the extreme volume values, Figure 2-12C. This is caused by a phase shift. When the volume has reached its extreme value the flow is zero. The pressure is then p_c, which is related to the compliance of the lungs. The difference between p_{max} and p_c is generally small, partly because the pressure change is not sinusoidal. The reversal of the flow occurs rather slowly in quiet breathing, thus flattening somewhat the pressure curve. Moreover, the pressure curve shows fluctuations because the pumping heart rhythmically exerts forces on the tissues surrounding the balloon. This makes it necessary to use mean values for the pressures.

The principle of the method to derive the subglottic pressure from the oesophageal pressures, is indicated in Figure 2-13.

When the volume at time t_0 passes the value V_{max}, the corresponding pressure in the oesophagus is p_{t_0}, with

$$p_{t_0} - p_c = p_s + p_r \qquad (2\text{-}7)$$

p_c is the pressure due to the compliance, p_s is the subglottic pressure and p_r is the product of the viscous resistance and the air flow rate during phonation.

The term p_r must be taken as a correction factor, which in most cases may be neglected. However, in cases of high flow values, neglecting p_r may introduce a systematical error.

For a flow of 200 ml/s, p_r is comparable with the random measuring error for subglottic pressure, i.e. about 50 Pa (0.5 cmH_2O).

Correspondingly, the subglottic pressure can be calculated at the moment the volume curve passes V_{min}. By interpolation the subglottic pressure can be calculated for every volume between V_{max} and V_{min}.

In calculating, there still are a few potential sources of error, which, however, appear to be of little importance:--

a. In Equation 2-7 no correction has been made for the resistance of the flowhead. The resistance of the flowhead (2.4.1.2) is 32.5 Pa.s/l (0.325 cmH_2O.s/l). The error due to this resistance is proportional to the air flow rate and negligible small.

b. If the pressure in the lungs is increased the lung volume is compressed and some water vapour condenses. If at a lung volume of 3000 ml the pressure is raised from 100 kPa to 100 kPa + Δp, the following Equation applies for the new volume V

$$\frac{(100 - 6.3)^2}{100} \times 3000 =$$

$$= \frac{(100 + \Delta p - 6.3)^2}{100 + \Delta p} \times V \qquad (2\text{-}8)$$

From this Equation

$V = 3000 - 34 \times \Delta p$ (6.3 kPa is the saturated vapour pressure at 37 ^{o}C). The lung volume is smaller and this

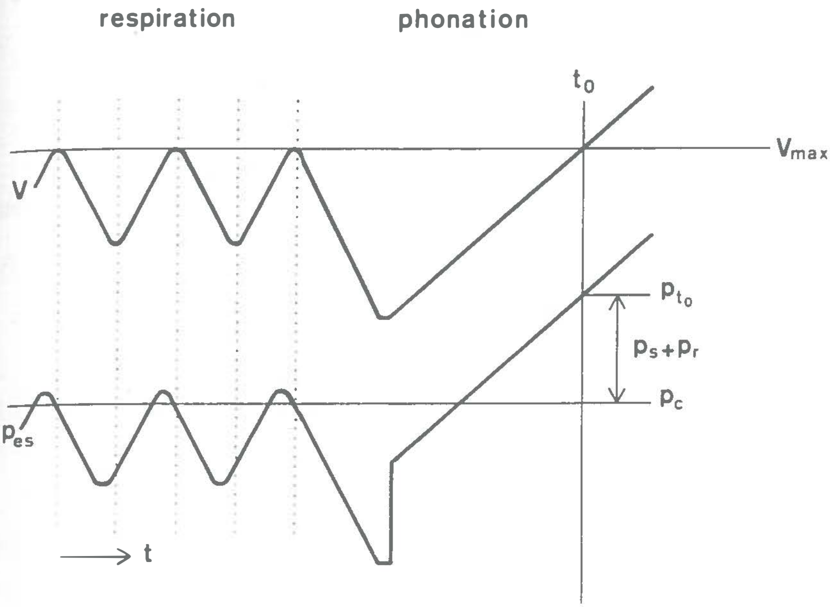


Figure 2-13. Principle of calculating subglottic pressure during phonation. At time t_o after the onset of phonation the value V_{max} is reached again. The pressure p_c, corresponding with volume V_{max}, should then be registered, if phonation had not begun. The actual pressure in the oesophagus at time t_o is p_{t_o}. The difference between p_{t_o} and p_c corresponds with the subglottic pressure during phonation p_s, plus a pressure p_r which equals the product of the viscous resistance and the air flow rate during phonation. The pressure p_r is negligible in normal lungs. Potential sources of error have been discussed already in the text.

goes along with a somewhat higher oesophageal pressure. This error is proportional to the lung volume and the subglottic pressure. At a lung volume of 3000 ml before the compression, the volume becomes 34 ml smaller after compression at a subglottic pressure of 1 kPa (10 cmH_2O). With a compliance of 2.5 l/kPa the measured subglottic pressure would be 14 Pa (0.14 cmH_2O) i.e. 1.4% too high. This may be neglected.

c. At raising the subglottic

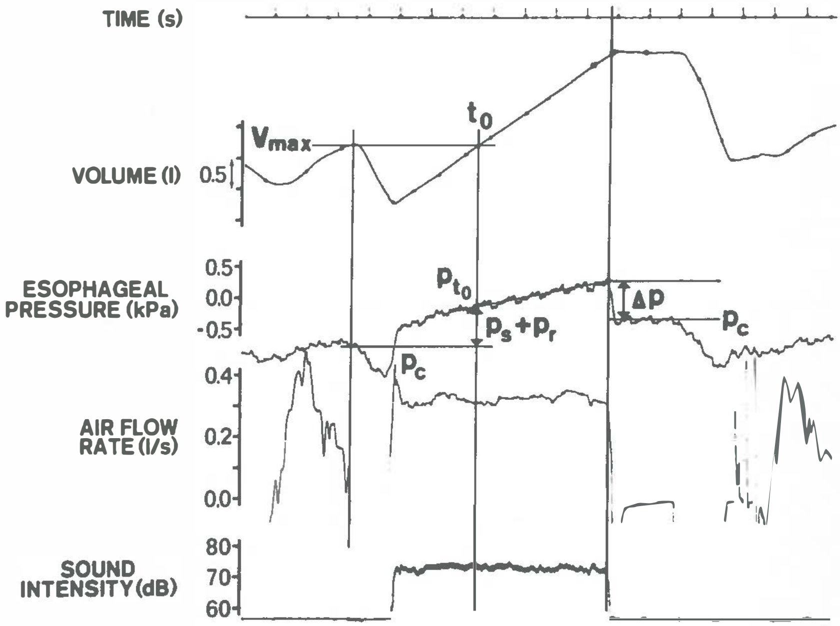


Figure 2-14. Verification of the indirect measuring method by abruptly stopping phonation. For a short moment after phonation the lung volume is kept constant with an open glottis. The pressure in the oesophagus drops to the value p_c corresponding with that lung volume. The pressure drop Δp equals $p_s + p_r$ (Figure 2-13). In calculating Δp, it is necessary to take account of the variations in consequence of cardiac activity.

pressure some blood will be pressed out of the lungs and this may have some influence on the compliance and the viscous resistance. This error will be proportional to the subglottic pressure, but is probably small.

2.7.2 Verification of the indirect method for determining subglottic pressure

The method described can be verified as follows: --

a. By abruptly stopping phonation and keeping the glottis open, maintaining the lung volume con-

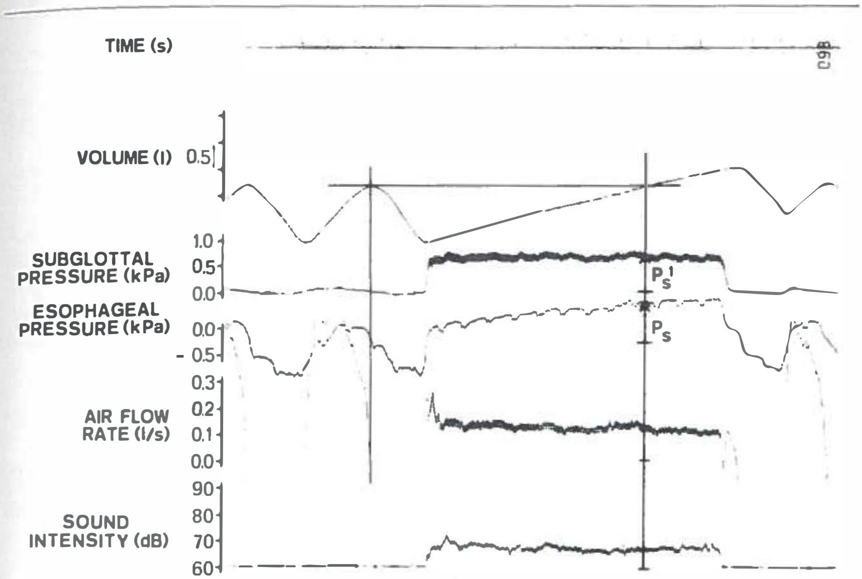


Figure 2-15. Verification of the indirect measuring method by simultaneous measurement of the subglottic pressure by a direct method. To measure the subglottic pressure directly, a hollow needle connected with a pressure transducer is inserted into the subglottic space.

stant, see Figure 2-14.

The oesophageal pressure sharply drops to the value corresponding to that volume. The pressure drop Δp, equals the subglottic pressure during phonation plus p_r.

The results of this method - which only can be applied with trained subjects - yielded satisfactory agreement between the two methods, since deviations remained within measuring errors.

b. By comparing the indirectly measured subglottic pressure with the simultaneous directly measured subglottic pressure.

Such a comparison could be carried out in three patients. The cricothyroid membrane was perforated by a hollow needle (18 gauge, Angiocath, Deseret Pharmaceutical Co., Inc., Sandy, Utah 84070, USA), the tip of the needle being brought into the subglottic space. The needle was connected to a pressure transducer by means of a catheter.

The results of 106 comparisons are shown in Figure 2-15 and Figure 2-16. The linear regression line

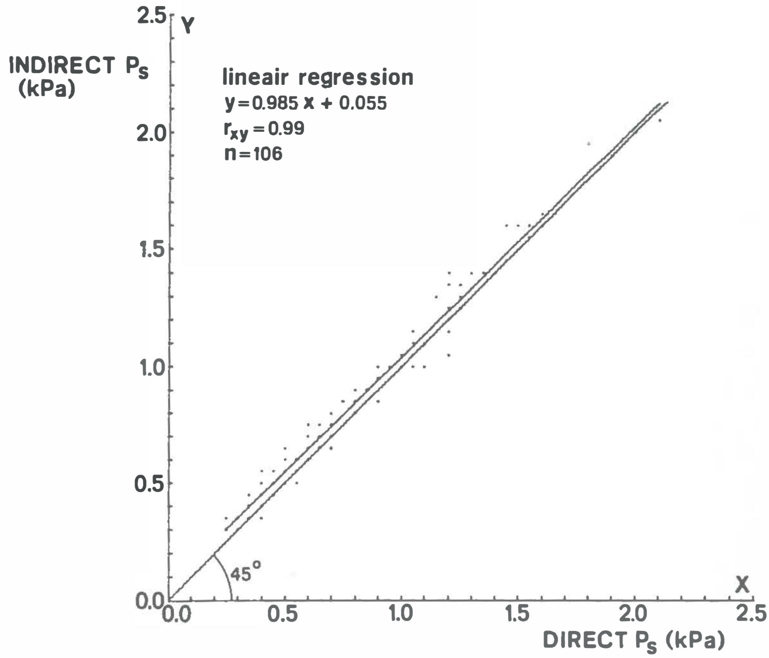


Figure 2-16. Comparison of subglottic pressure values, simultaneously measured with a direct method and with our indirect method in three patients.

is associated with a correlation coefficient of 0.99. The shift of the line corresponds with a systematical error of about 50 Pa (0.5 cmH_2O), corresponding with the expectations based on neglecting the pressure p_r.

2.7.3 Automatic correction for the compliance of the lungs

During our investigation a device for automatic correction for the compliance of the lungs was designed and built in the Groningen University Laboratory for Medical Physics.

Mead and Whittenberg (1953) had previously introduced a method for compliance correction. This method we have implemented for our apparatus using an adjustable constant fraction of the volume signal to inversely control the pressure signal, see Figure 2-17.

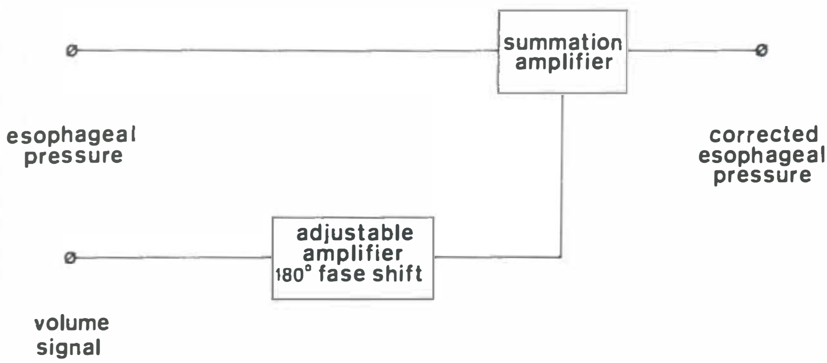


Figure 2-17. Diagram of the set up for the automatic correction method used for the lung compliance.

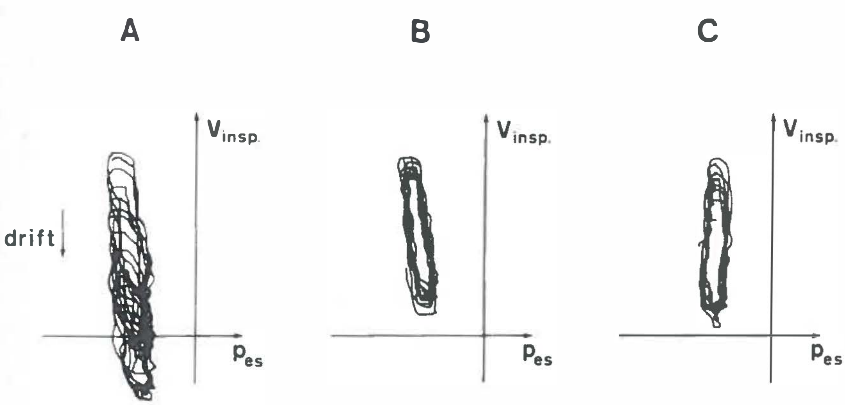


Figure 2-18. Diagrams of p_{es}-V loops demonstrating the effect of the correction methods.

A. Without correction

B. With expiration flow correction (2.5.2.2)

C. With expiration flow correction and compliance correction (2.7.3).

It may be assumed that the compliance is constant within the range of the volumes, provided that during the measurements the person neither inspires nor expires too deeply. At the level of V_{max} (i.e.

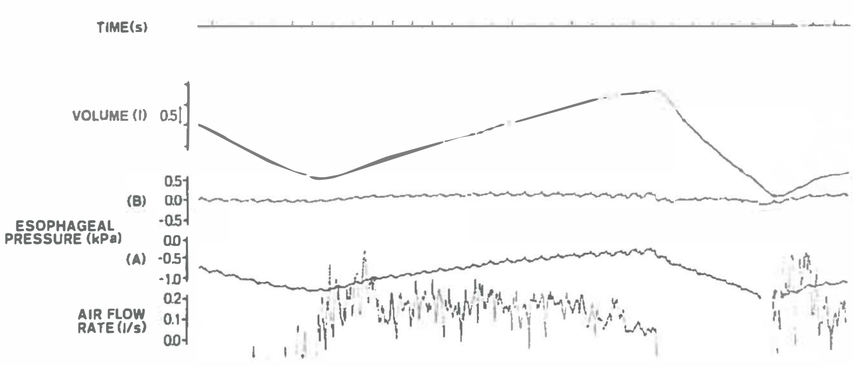


Figure 2-19. Effect of the automatic compliance correction during respiration. The curves were registered in a subject asked to expire slowly after an inspiration. Curve A shows the directly represented variations of oesophageal pressure, while the simultaneously obtained oesophageal pressure curve after the automatic compliance correction (2.7.3) was recorded in curve B.
The variations in curve A are mainly due to changes related to the compliance. The remaining variations in curve B are the consequence of the viscous resistance and the momentary value of the air flow rate. The running mean values of the pressure during the respiration shown in curve B represents a zero subglottic pressure. This zero value may also be obtained by holding the breath with an open glottis, the corrected pressure in that case will represent zero.

the Functional Residual Capacity level) the compliance curve is linear. The fraction of the volume signal needed for proper correction has to be determined experimentally for every individual person. The individual value of the compliance can be derived from the value of the required fraction.

When the adjustment is correct the loop in the p_{es}-V diagram will be vertical, see Figure 2-18B and C. The corrected oesophageal pressure will then show only small variations due to the viscous resistance and will be proportional to the momentary value of the air flow rate, see Figure 2-19. After proper adjustment the corrected oesophageal pressure will remain at a constant level during quiet breathing.

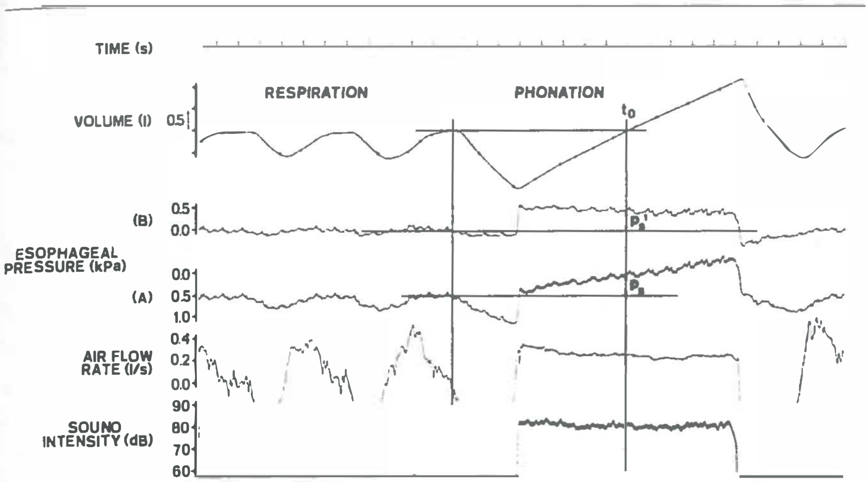


Figure 2-20. Effect of the automatic compliance correction during phonation. The curves were recorded in a subject asked to phonate after a few quiet respirations. In this Figure p_s has been determined at time t_o (neglecting the viscous resistance) to compare with p'_s, i.e. the subglottic pressure determined at the same moment from the corrected pressure. From the automatically corrected pressure curve the subglottic pressure can be read at each moment during phonation.

During phonation the pressure is increased by an amount which equals the corresponding subglottic pressure, see Figure 2-20. The errors discussed under 2.7.1 may of course play an additional role.

The automatic correction greatly simplified the elaboration of the curves, as the subglottic pressure during phonation is simply equal to the increase in the corrected oesophageal pressure.

Drift during phonation is recognized immediately from the level of the corrected pressure in quiet breathing before and after phonation.

Since the automatic correction device was constructed during the last phase of our investigation, nearly all subglottic pressures were determined by the method described in 2.7.1.

Chapter 3 Analysis of curves and processing of experimental data

3.1 Introduction

In most cases the measurements were performed after the subjects had first visited our outpatients department, where a subject protocol was taken down based on general observation and mirror examination, sometimes including stroboscopy. Before the measuring series was started, thus data were available inter alii about the subjects vocal potentialities (phonetogram) and average speaking voice pitch level.

Mostly at the end of an expiration, the subject was asked to take a breath and to start phonation. The required pitch was indicated, starting with a pitch and a sound intensity that could be easily produced by the subject. When the entire intensity range of all pre-selected pitches has been examined, the measuring equipment was checked.

Before the automatic correction for the compliance was available, the curves were graphically elaborated. The principle of this method has been discussed in 2.7.1 and is illustrated by Figure 3-1.

Graphic elaboration of the curves is not possible during the measuring series, as it takes quite some time and therefore has an inhibiting influence on the progress of the measuring series. With the automatic correction of the oesophageal pressure for the compliance of the lungs, the data can be taken from the curves during the series and eventually filled in in a graph. If desired, additional measurements at any pitch and intensity could be carried out immediately.

The rejection of curves inapt for use will further be discussed in 3.2.

The determination of experimental data will be described in 3.3.

In 3.4 the processing of the data and calculation of the efficiency will be described.

Finally the presentation and comparison of measuring results will be discussed in 3.5 and 3.6.

3.2 Rejection of curves

Sometimes curves had to be rejected as not usable to determine the subglottic pressure, e.g. in the case of a contraction of the oesophagus.

The curves sometimes show deviations in consequence of various conditions. These ought to be recognized at the time of the measuring series, so that, if an artefact occurs, the phonation can

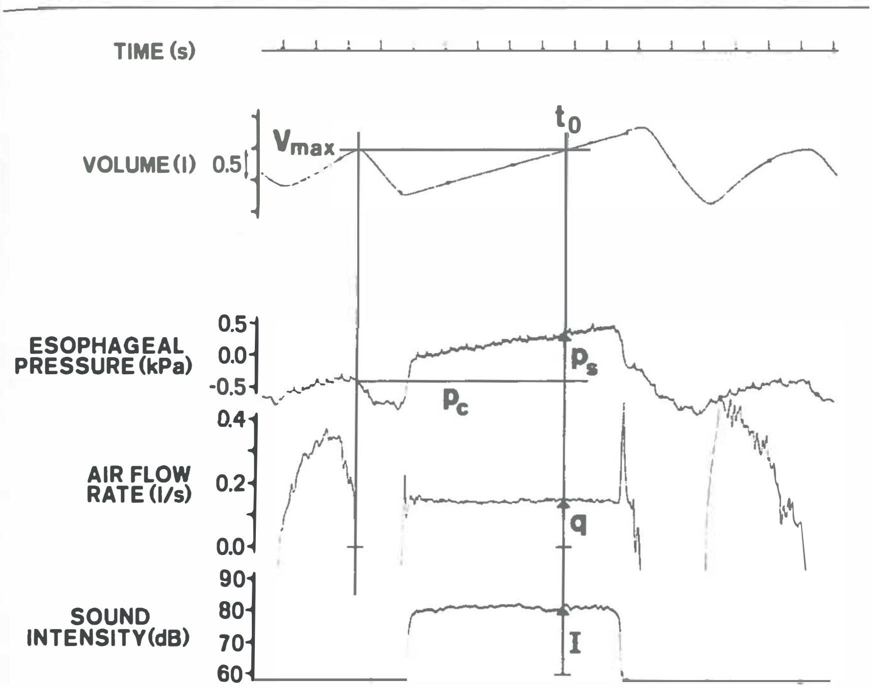


Figure 3-1. An example of an usable registration, without correction for the mechanical properties of the lungs. The point of time t_o and the reference oesophageal pressure p_c are ascertained by reference to V_{max}. The difference between the oesophageal pressure at the time t_o and the reference pressure p_c is the subglottic pressure p_s (neglecting p_r). For the same point of time, the sound intensity I and the mean air flow rate q are determined.

be repeated at the same pitch and intensity. The frequency of artefacts per series varies and is unpredictable.

The insertion of the balloon may induce contractions of the oesophagus, but for the most part these subside after a short time, permitting an usable curve to be obtained.

In Figure 3-2 four examples are represented of not usable registrations.

a. Figure 3-2A. Without compliance correction.

Here, the subject inspired too shallow to pass the point V_{min} and then stopped phonation before point V_{max} was reached. In such cases, instructions were given and the phonation was repeated.

b. Figure 3-2B. Without compliance correction.

Just before phonation the subject had swallowed. The air passage was blocked for a short time (no flow) and after that a powerful contraction of the oesophagus followed, making the pressure curve not usable during a 7 seconds interval.

c. Figure 3-2C. Without compliance correction.

Here, the pressure curve shows the effect of the presence of air in the oesophagus. During quiet breathing the oesophageal pressure varies between limits determined by the mean resting pressure in the oesophagus (which is negative), the compliance of the lungs and the tidal volume. When the reference oesophageal pressure p_c (Figure 3-1) has been determined, p_c should be within these limits. A deviating value may be the result of an increased mean resting pressure in the oesophagus, caused by the presence of air in the oesophagus. The person will notice this as such. The air can be made to escape by deep sighing or belching.

d. Figure 3-2D. With and without compliance correction.

Here, a pressure artefact is shown during phonation. A certain course of the curves can be expected. For example, in phonation with a constant sound intensity and a constant flow, the oesophageal pressure will slowly increase. Sometimes during phonation an easily recognizable little contraction of the oesophagus occurs. In Figure 3-2D this happened just at the moment for determining the reference pressure p_c. The curve without correction for the compliance cannot be elaborated. The advantage of the corrected oesophageal pressure is obvious. The phonation can be used for the periods before and after the contraction.

3.3 Collection of data

For the elaboration of the curves a standard protocol is used. With the aid of calibrated scales, the data for air flow rate, subglottic pressure, and sound intensity can be read without conversion.

The reading precision for the sound intensity is $\pm$ 0.5 dB, for the air flow rate $\pm$ 2.5 ml/s and for the oesophageal pressure $\pm$ 25 Pa (0.25 cmH_2O).

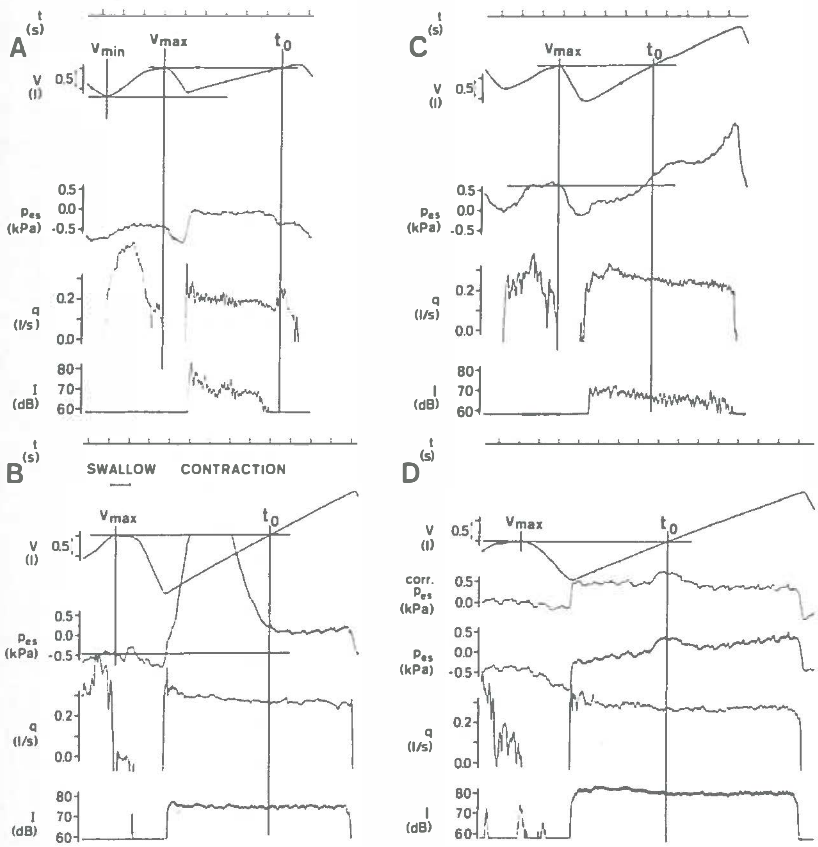


Figure 3-2. Examples of curves not usable for elaboration, see text.

Taking into account the fluctuations of the curves, the measured values for the intensity are rounded off to multiples of 1 dB and those of the flow to multiples of 5 ml/s.

In determining the data for the oesophageal pressure, the rhythmic variations as a result of cardiac activity must be taken into account. Therefore a mean value is assessed and taken down in multiples of 50 Pa (0.5 cmH_2O).

3.4 Processing of data. Calculation of efficiency

The measured values for air flow rate, subglottic pressure, and intensity, together with the values for the pitch and the average speaking voice pitch level, are transferred to a computer system for further processing. For every series some administrative items are added. By using the computer the calculation of the efficiency is easier and the results can be compared with each other and with reference values.

Calculation of efficiency.

The efficiency E of the glottis generator is calculated by relating the produced sound power, P_{acoust}, to the subglottic power supplied to the larynx, P_{subgl}. Represented in a formula:

$$E = \frac{P_{acoust}}{P_{subgl}} \qquad (3\text{-}1)$$

For the calculation of the produced sound power P_{acoust} we start from an approximation, already mentioned in 2.3.2.

The subglottic power P_{subgl} is calculated by multiplying the mean air flow rate by the mean subglottic pressure.

A numerical example.

Given: an instance of phonation with a sound intensity I of 75 dB measured at a distance r of 15 cm in front of the outlet of the flowhead, the air flow rate q being 200 ml/s, the subglottic pressure p being 1 kPa (10 cmH_2O).

$$\begin{aligned} P_{acoust} &= 2 \times \pi \times r^2 \times 10^{\frac{I}{10}} \times 10^{-12} \\ &= 2 \times \pi \times (0.15)^2 \text{ m}^2 \times \\ &\quad \times 10^{7.5} \times 10^{-12} \frac{\text{W}}{\text{m}^2} \\ &= 4.47 \times 10^{-6} \text{ Watt} \\ &\approx 4.5 \times 10^{-6} \text{ Watt} \end{aligned}$$

$$\begin{aligned} P_{subgl} &= \bar{q} \times \bar{p} \\ &= 200 \frac{\text{cm}^3}{\text{s}} \times 1 \text{ kPa} \\ &= 2.10^{-4} \frac{\text{m}^3}{\text{s}} \times 10^3 \frac{\text{N}}{\text{m}^2} \\ &= 2.10^{-1} \times \frac{\text{Nm}}{\text{s}} \\ &= 0.2 \text{ Watt} \end{aligned}$$

Then, substituting these values in Equation 3-1, we may write

$$\begin{aligned} E &= \frac{4.5 \times 10^{-6}}{2 \times 10^{-1}} \\ &= 2.25 \times 10^{-5} \end{aligned}$$

This numerical example can be extended by an analysis of the propagation of errors in the calculation of the efficiency.

If Z is the product (or quotient) of A and B, and ΔA is the error in A, ΔB the error in B, the error

Table 3-1. Experimental data obtained from a normal male subject for air flow rate and subglottic pressure at various sound intensities measured at a pitch of E3 (165 Hz). In the last column, the calculated efficiency values have been given. The dynamic range was 28 dB. The average speaking voice pitch level was C3 (125 Hz). The number of measured data was nine, and the calculated regression lines are represented in Figure 3-4.

intensity I in dB	mean flow q in ml/s	mean subgl. pressure p in kPa (10 cmH_2O)	efficiency E in $x10^{-5}$
60	90	0.25	0.6
64	95	0.25	1.5
64	120	0.25	1.2
70	180	0.35	2.2
73	165	0.3	5.7
78	200	0.5	8.9
79	220	0.6	8.5
88	380	0.8	29.3
88	450	1.0	19.8

ΔZ satisfies

$$\left(\frac{\Delta Z}{Z}\right)^2 = \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2$$

The subglottic power P_{subgl} is the product of the mean flow and the mean pressure,

$$\left(\frac{\Delta P_{subgl}}{P_{subgl}}\right)^2 = \left(\frac{\Delta\bar{q}}{\bar{q}}\right)^2 + \left(\frac{\Delta\bar{p}}{\bar{p}}\right)^2$$

$$= \left(\frac{2.5}{200}\right)^2 + \left(\frac{50}{1000}\right)^2$$

$$= 0.028^2$$

Thus, the percentage error may be said to be about 3%.

The percentage error in P_{acoust} is due to the inaccuracy of measuring sound intensity. A variation of $\pm$ 0.5 dB means a variation of $\pm$ 12%.

The percentage error in the efficiency is thus

$$\frac{\Delta E}{E} = \pm\sqrt{0.12^2 + 0.5^2}$$

$$= \pm\ 0.13 \quad \text{or} \quad 13\%$$

The error in the final result is mainly determined by the sound intensity measurement error. At low subglottic pressures, e.g. 0.5 kPa (5 cmH_2O) the error in the efficiency runs to about 15%.

3.5 Presentation of data; regression lines

A measuring series generally is composed of 40-50 phonations, distributed over various frequencies.

For every phonation at a certain frequency and sound intensity, the experimental data for air flow rate and subglottic pressure are given in ml/s resp. kPa. The calculated efficiency is given in 10^{-5}, see Table 3-1.

Because of the presence of random deviations the raw experimental values cannot be used very well for comparison with reference values or for comparison of results of several measuring series with each other.

In order to eliminate these random deviations as much as possible, the data of a group of phonations, e.g. for the same pre-selected frequency, were processed in a scatter diagram. On the horizontal axis we find the sound intensity and, on the vertical axis, the air flow rate, subglottic pressure, or efficiency.

The sound intensity on the X-axis is taken as the independent variable and the values represented on the Y-axis as the dependent variables.

The relation between the variables can be described by computing a curve through the measuring points.

From our own preliminary studies and from the literature (Van den Berg, 1956; Koike and Hirano, 1968) it appeared that the relation can be described fairly well by a straight line if the logarithms of the dependent variables are used.

The computing of the curves is therefore restricted to the determination of the best fitting straight line through the experimental data. Such a line usually is called a regression line.

The values of the intensity will be indicated as x; the transformed values of flow, pressure, or effiency as y, see Figure 3-3.

The Equation for the regression line is then:

$$y_e = a + bx \qquad (3\text{-}2)$$

in which $y_{e(stimate)}$ is the best estimate of the transformed value, x is the intensity value in dB (which in itself is already logarithmic).

The coefficient a determines the height of the line, while the value of a can be read from the point of intersection of the regression line and the Y-axis.

The regression coefficient b represents the slope of the line; a positive value of b means an increase (for example of the subglottic pressure) at increasing intensity.

If the values of a and b are known, an estimate can be made of the flow, subglottic pressure, or efficiency at a certain intensity by calculating the corresponding value of y_e with Equation 3-2.

The determination of the best fitting straight line through the experimental data, with the calculation of a and b, is based on the least-squares method described in manuals on statistics (Armore, 1967; Snedecor and Cochran, 1968; Bevington, 1969; Sokal and Rohlf, 1969; Wyvekate, 1972). The regression line is computed in such a way, that the sum of the squares of the individual deviations from this line is minimal.

The residual spread is represented by the so-called Estimated Standard Deviation of Error, short e.s.d.e. This measure denotes the dispersion around the regression line.

After the transformation and the calculation the experimental data and the regression line are displayed graphically with a computer

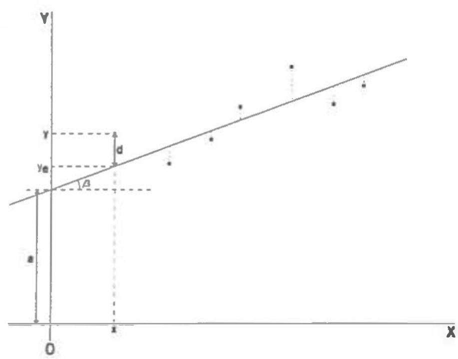


Figure 3-3.
Determination of the regression line: the best fitting straight line drawn through a number of measured data. The line is defined by the formula $y_e = a + bx$, in which a indicates the height of the line and b the slope of the line, i.e. the tangent of the angle of inclination β. The line has been computed in such a way that the sum of the squares from the distances d, the vertical distances from the measuring points to the line, is minimal.

controlled X-Y recorder, and the values of a, b, and e.s.d.e. are printed out.

The regression line is only applicable for intensity values within the dynamic range of the voice at a certain frequency. Therefore,

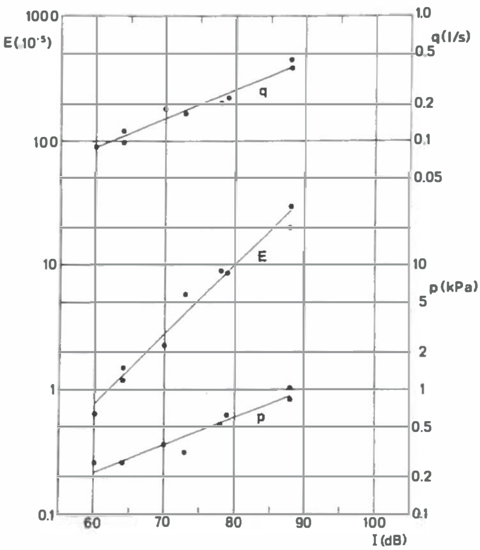


Figure 3-4.
Regression lines for the experimental data given in Table 3-1.

in plotting the regression line only that part of the X-axis is used which corresponds with the dynamic range of the voice. Extrapolation outside this range is meaningless.

The regression line is regarded as an average of the measured values, see Figure 3-4. In this figure, the experimental data and the corresponding regression lines are depicted for the data of Table 3-1.

3.6 Comparison of data with the aid of regression lines: characteristic values for the middle of the intensity range

The regression lines are especially useful for comparing the results of several different measuring series.

In Table 3-2, experimental data are given as obtained in examining a patient. Figure 3-5 gives the regression lines together with the corresponding reference regression lines as obtained for normal subjects, see Chapter 4. For the entire dynamic range, the flow regression line as well as that of the subglottic pressure lies at a higher level than the reference regression line. Consequently, the efficiency regression line lies below the reference regression line for the entire dynamic range.

In comparing efficiencies of various voices at identical intensity values, on principle a comparison is made of the values of the subglottic power supplied. It is common practice to use the decibel measure for a comparison of power values.

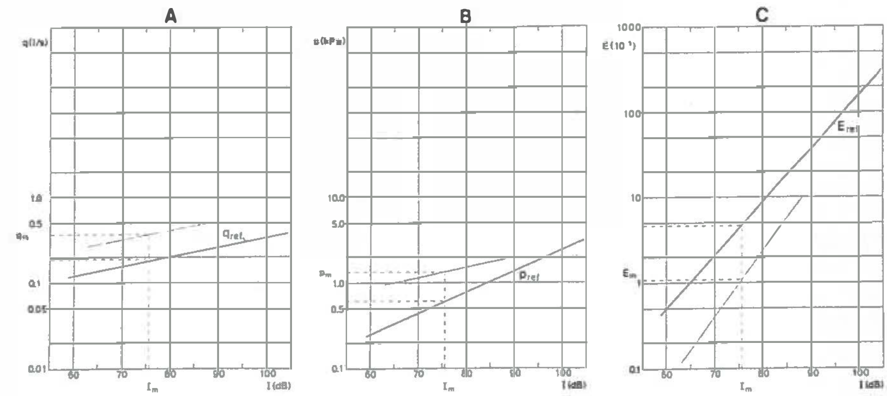
By using a decibel division along the Y-axis, the difference with another efficiency regression line

Table 3-2. Experimental data obtained from a female patient for air flow rate and subglottic pressure at various sound intensities measured at a pitch of A3 (220 Hz). In the last column, the calculated efficiency values have been given. The dynamic range was 25 dB. The average speaking voice pitch level was A3 (210 Hz). The number of measured data was 19 and the calculated regression lines are represented in Figure 3-5.

intensity I in dB	mean flow q in ml/s	mean subgl. pressure p in kPa (10 cmH_2O)	efficiency E in $\times 10^{-5}$
63	340	0.95	0.1
64	180	0.8	0.2
66	250	0.95	0.2
67	370	1.25	0.2
68	200	1.1	0.4
70	410	1.6	0.2
71	325	1.1	0.5
73	300	1.0	0.9
74	300	1.15	1.0
74	410	1.2	0.7
74	375	1.2	0.8
75	470	1.1	0.8
76	440	1.2	1.1
77	450	1.3	1.2
78	390	1.25	1.8
78	360	1.5	1.7
80	330	1.55	2.8
84	350	1.55	6.6
88	520	2.1	8.2

at a certain sound intensity may be read directly in decibel, see Figure 3-6.

In comparing regression lines with each other and with the corresponding reference regression line, it is meaningful to compare the data for the intensity value I_m belonging to the middle of the dynamic range, as it may be assumed that the values for air flow rate, subglottic pressure, and efficiency



AIR FLOW RATE (l/s)

I_m = 75.5 dB

q_m = 0.36

Ref.value = 0.185

b = 1.097×10^{-2}

Ref.value = 1.15×10^{-2}

SUBGLOTTIC PRESSURE (kPa)

I_m = 75.5 dB

p_m = 1.32

Ref.value = 0.6

b = 1.198×10^{-2}

Ref.value = 2.5×10^{-2}

EFFICIENCY ($\times 10^{-5}$)

I_m = 75.5 dB

E_m = 1.1

Ref.value = 4.61

b = 7.704×10^{-2}

Ref.value = 6.3×10^{-2}

Figure 3-5. Depiction of the method for comparison of measuring results with the aid of regression lines. For the sake of clarity, the data for flow, pressure, and efficiency are each represented separately in a diagram; in most cases, in this work, these data are all represented in the same figure. The experimental data used for determination of the regression lines of the patient were recorded in Table 3-2. The reference values belong to an intensity in the middle of the dynamic range (I_m), see Chapter 4, Figure 4-12.

at I_m are in general representative for voice production.

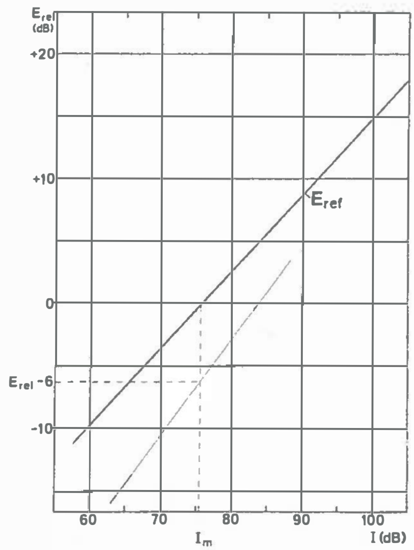
The dynamic range and its middle are also plotted by the computer in the tables. The calculated values for air flow rate, subglottic pressure, and efficiency at I_m are indicated as q_m, p_m, and E_m, respectively.

Comparison with the reference regression line always takes place at the intensity value I_m of the individual regression line. For the efficiency, the difference is recorded as E_{rel} (in dB). The values E_{rel} enable us to compare individual regression lines. In doing so the influence of differences in I_m between the measuring series is eliminated in a first approximation.

The difference between E_{rel} values is indicated as ΔE_{rel}.

The regression coefficient b, which determines the slope of the line, sometimes deviates only little from zero. In the tables, the value of b = tanβ (Figure 3-3) therefore is given after multiplication by a factor 100.

In evaluating the result of a given therapy to a patient, it may happen that the dynamic ranges of successive measuring series are not identical. In such a case, the



EFFICIENCY (x 10^{-5})

I_m = 75.5 dB

E_m = 1.1

Ref.value = 4.61

b = 7.704 x 10^{-2}

Ref.value = 6.3 x 10^{-2}

E_{rel} = -6.3 dB

Figure 3-6.
The reference regression line for the efficiency based on the combined experimental data from a number of normal subjects (see Chapter 4) displayed together with the efficiency regression line from one patient (Table 3-2). The difference in efficiency (E_{rel}) at a certain intensity can be read directly in dB.

Table 3-3. Characteristic values for the experimental data in the middle of the dynamic range for air flow rate, subglottic pressure, and efficiency as recorded in Table 3-1 and Table 3-2.

	number of data	dyn.range dB	I_m dB	b $x10^{-2}$	a	e.s.d.e.		
FLOW							q_m ml/s	
Normal Subj. Table 4-1	9	60 - BB	74	2.31	0.558	0.06	185	
Patient Table 4-2	19	63 - 88	75.5	1.097	1.729	0.1	361	
SUBGLOTTIC PRESSURE							p_m kPa	
Normal Subj. Table 4-1	9	60 - 88	74	2.175	-1.974	0.07	0.43	
Patient Table 4-2	19	63 - 88	75.5	1.198	-0.786	0.06	1.32	
EFFICIENCY							E_m $x10^{-5}$	E_{rel} dB
Normal Subj. Table 4-1	9	60 - 88	74	5.515	-3.424	0.1	4.5	0.9
Patient Table 4-2	19	63 - 88	75.5	7.704	-5.784	0.13	1.1	-6.3

fact that the dynamic range is larger or smaller also is significant and ought to be considered in establishing a conclusion.

Summarizing:

The result of the calculations for the characteristic values a, b, I_m, q_m, p_m, E_m, and E_{rel}, and e.s.d.e. are written out by the computer after computing the regression lines from the experimental data.

In Table 3-3 these characteristic values are given for the experimental data from the Tables 3-1 and 3-2.

Chapter 4 Investigation conducted in normal subjects: reference values

4.1 Introduction

For evaluation of experimental data from patients, reference values are required. In order to obtain such values, measurements were performed in men and women who never had troubles with their voices. The measurements were performed in the same way as in patients.

A survey of the normal subjects is given in 4.2.

In section 4.3, the reproducibility of measurements in the same subject is discussed.

The set of the regression lines from all normal subjects forms a reference area for evaluating the regression lines of patients. These reference areas for flow, pressure, and efficiency will be discussed in 4.4.

In 4.5, the results on the group of normal subjects are compared with data from the literature for flow, pressure, and efficiency.

In 4.6, the aerodynamical differences between breathy and non-deviant phonations in the same normal subject are discussed.

4.2 Survey of the normal subjects

The group of normal subjects consisted of 30 males and 33 females. They were recruited from volunteers: co-workers of the E.N.T. Department, medical students, and students from the training-centre for speech therapists. None of these subjects ever had any vocal complaints. Laryngeal abnormalities were not observed; the compass of the voice was at least two octaves.

In these 63 people, 93 measuring series were performed, with usable sets of curves for 4267 single instances of phonation. Phonations judged by trained listeners to be vocally disturbed, e.g. breathy, hoarse, or hyperkinetic, were discarded. If less than 10 phonations per measuring series were left, the whole series was put aside. This reduced the group to 45 normal subjects (24 males and 21 females). In 4.4.4 we shall discuss the aerodynamic characteristics of the discarded phonations.

The age of the men varied from 20 to 65 years, averaging 31 years. The age of the women ran from 17 to 32 years, averaging 23 years. From the 45 normal subjects 72 usable series were obtained; 17 subjects came for 2 series, 2 for 3 and 1 for 7 series.

Table 4-1A and 4-1B give a survey.

Table 4-1A. Subject protocols for the 24 normal male subjects, with respect to age, number of measuring series, average speaking voice pitch level (f_{mean}), and number of phonations in the successive measuring series. The total number of measuring series was 43, comprising a total of 1917 instances of phonation at various pitches and intensities.

Subject No.	age years	number of series	f_{mean} Hz	number of phonations in successive measuring series
1	26	3	110	34 89 46
2	31	7	125	45 45 60 87 49 28 30
3	32	2	110	41 95
4	31	1	110	21
8	20	2	100	19 29
12	22	2	95	57 43
13	39	2	130	25 49
16	20	2	135	47 43
17	24	2	125	73 78
18	27	2	100	51 65
21	20	1	110	25
24	21	1	100	39
25	20	1	130	34
31	23	1	110	30
35	30	2	120	27 38
38	23	1	120	24
44	24	1	90	48
46	36	1	130	38
47	31	1	100	23
55	24	1	90	46
60	56	1	95	30
61	65	2	95	34 46
62	52	3	125	35 50 19
63	47	1	110	82

Table 4-1B. Subject protocols for the 21 normal female subjects, with respect to age, number of measuring series, average speaking voice pitch level (f_{mean}), and number of phonations in the successive measuring series. The total number of measuring series was 29, comprising a total of 829 instances of phonation at various pitches and intensities.

Subject No.	age years	number of series	f_{mean} Hz	number of phonations in successive measuring series
5	26	1	200	22
9	24	2	220	27 26
10	19	2	220	17 16
11	19	1	210	30
15	24	1	220	38
19	17	1	220	37
22	22	1	220	43
26	20	2	195	18 21
27	29	2	220	24 36
28	21	2	220	46 39
29	25	1	220	32
30	22	2	220	36 28
32	25	1	220	17
40	32	1	200	11
41	25	1	220	18
49	25	2	200	37 32
50	27	2	200	19 25
51	21	1	200	44
52	20	1	200	23
54	21	1	220	27
56	19	1	195	30

4.3 Reproducibility of phonations of a normal subject

The usefulness of reference values as a criterion depends on the reproducibility of the experimental results. A certain variation is of course unavoidable.

The number of suitable phonations in a measuring series is important, as the uncertainty gets less if more points determine the path of the regression line.

First, the reproducibility was determined for a great number of phonations (about 100) with identical target intensity and target fundamental frequency. For this purpose, four measuring series were performed in three normal Subjects (Nos. 2, 8, and 24), see 4.3.1.

The accuracy with which a certain regression line fits the experimental data is indicated by the Estimated Standard Deviation of Error (e.s.d.e.). On the basis of these values, we considered a further reduction of data.

It appeared to be a permissable approximation to describe all results by three regression lines. This matter will be discussed further in 4.3.2.

Comparisons were made of these three regression lines per measuring series for one subject at different times. These series were carried out with twenty normal subjects at different time intervals, ranging from 1 day to about 4 years (between the first and the seventh measuring series with Subject No. 2). This shows within which limits in one subject the regression line lies, if the measurements have been repeated under possibly equivalent circumstances. This is of course of great importance in the assessment of the effect of medical treatment. The results will be discussed in 4.3.3.

4.3.1 Reproducibility of phonations within one measuring series in one (single) subject

The reproducibility and the degree of variations in the aerodynamic data were investigated in a number of separate experiments. We asked the subject to try to make every phonatory adjustment alike to enable us to determine the degree of involuntary or physiological deviation. Because for each phonation the subject inspired at least once, the larynx had to be adjusted again every time for

Table 4-2. Results of tests of the reproducibility of measurements of phonations during one measuring series from one single person. The intensity measurement was made with an accuracy of ± 0.5 dB. The coefficient of variation was defined as the standard deviation divided by the mean, expressed as a percentage. Between the two measuring series of Subject No. 2, there elapsed a period of seven months.

Subject No.	freq. Hz	intens. dB	number of phonations	coëfficient of variation in % flow	press.	subgl. power	effic.
2	125	74 - 76	79	17	10	24	28
2	165	77 - 81	108	12	14	22	25
8	110	74 - 77	102	17	14	17	21
24	165	74 - 78	114	17	16	26	29
			mean	16	14	22	26

the required pitch and intensity. This did not happen always in exactly the same way, as might be expected. For our purpose, it was important to know how accurately the subject was able to reproduce the same laryngeal adjustment.

Four measuring series were performed, with three subjects instructed explicitly to repeat exactly the required laryngeal adjustment. The pitch remained the same and in every phonation the required intensity was adjusted by the subject as precisely as possible. Phonation took place at a pitch and intensity experienced by the subject as comfortable. The subjects were informed of the purpose of these measurements and intentionally tried to keep the variations as little as possible. Per measuring series we obtained about 100 phonations. The data for flow, pressure, subglottic power, and efficiency were averaged per measuring series, and the standard deviation was determined. From this, coefficients of variation were calculated. These calculations have been made with non-transformed values. The result is represented in Table 4-2.

From this table it appears that the variation coefficients for flow and subglottic pressure average respectively 16% and 14%. The value for the variation coefficient of the efficiency is remarkably high. We expected though that at a higher pressure value a lower flow value would be observed and vice versa. In the computing of the product of pressure and flow values the variation coefficient for efficiency would then be lower as a result of a compensating action. Only in Subject No. 8 did this appear more or less to be the case. In the two series from Subject No. 2 and in the series from Subject No. 24, there was no compensating action.

The variation coefficient for the efficiency averages 26%. Starting from the variation coefficients of the values for flow and pressure, an expected variation coefficient can be calculated by addition of the squares of the variation coefficients, in the assumption that flow and pressure are independent of each other. The computed variation coefficient amounts to 21%. This is lower than the variations present in the measured efficiency values. Therefore may at least be concluded that the reciprocal compensating action of flow and pressure is not very strong.

The established variation coefficients are rather great, though we asked the subject to phonate as much as possible in the same way. The deviation of the experimental data is partly caused by difficulties in maintaining the sound intensity at the required level. For every measuring series a certain intended value for the sound intensity has been selected. During phonation the intensity values varied around the intended value. These variations could not be avoided. At the elaboration of the curves the intensity values were rounded off and classified in intervals of 1 dB. This seems to be reasonably accurate, but it means a variation of 26%. This dispersion of course also has an influence on the values for flow, pressure, and efficiency.

The observed independence of flow and pressure, occurring at least in three out of four measuring series, is of significance for the theory of voice production. A high subglottic pressure is obviously not accompanied by a low air flow rate in every larynx. This also means that a phonation with a high air flow rate is not necessarily accompanied by a low subglottic pressure.

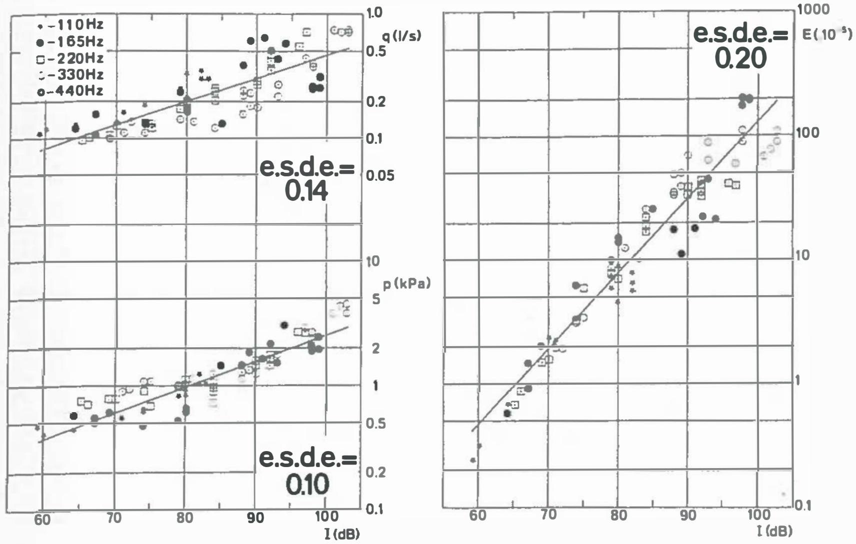


Figure 4-1. Depiction of the experimental data and regression lines for flow, pressure, and efficiency from the second measuring series from Subject No. 17. The experimental data from 78 instances of phonation at five various pitches have been represented. The values for the residual spread, i.e. the estimated standard deviation of error, e.s.d.e., have been mentioned in the figure. It is clear that the experimental data at the various pitches can hardly be distinguished from each other.

4.3.2 Regression line for phonations in one measuring series from one single subject

The observed dispersion of the experimental data at the same adjustment of the larynx (4.3.1) is also present in phonations at other pitches and intensities.

In one measuring series, data for several laryngeal adjustments for pitch and intensity are obtained.

Values measured at various pitches appeared to lie near each other, if they were brought together in one graph, see Figure 4-1.

Therefore the question arises whether it would be meaningful to study these measuring results separately.

The dispersion of the experi-

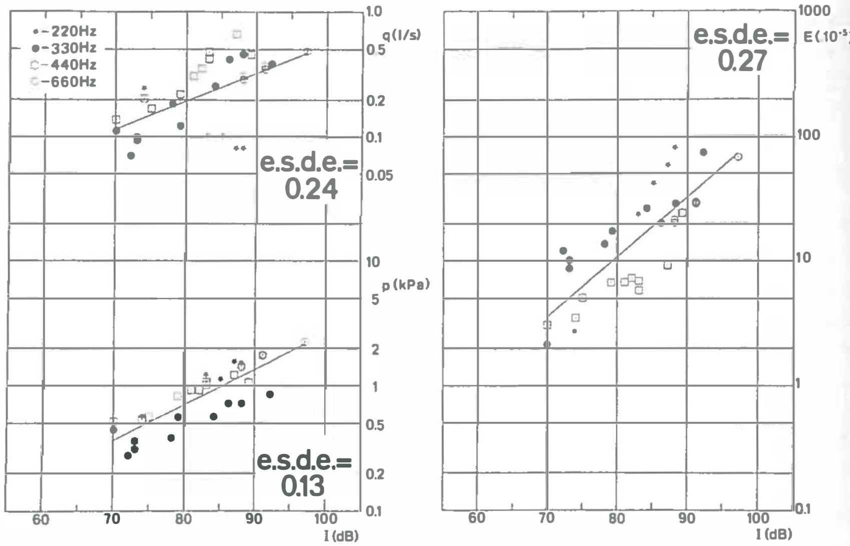


Figure 4-2. Depiction of the experimental data and regression lines for flow, pressure, and efficiency from Subject No. 11. Regression lines for the complete measuring series have been represented. A fairly high value has been found for the e.s.d.e. for flow and efficiency, see text.

mental data is partly due to the fact that not every phonation has been produced in the most efficient way (see also 4.4.4 and 4.6). The subject was left free in this respect.

The acceptability of working with only one regression line for the entire measuring series, regardless of the varying pitches, was studied. Accordingly, we made use of the fact that the smaller the e.s.d.e. is, the better the regression line fits the experimental data.

The data from the measuring series of all normal subjects have been recorded in Table 4-3 (Appendix).

It is of course impossible to trace the influences on the e.s.d.e. in all subjects. We had to restrict ourselves to give some examples and analyse cases with a high and low value for the e.s.d.e.

The dispersion of the experimental data around the regression line varies considerably.

It diverges for the flow from

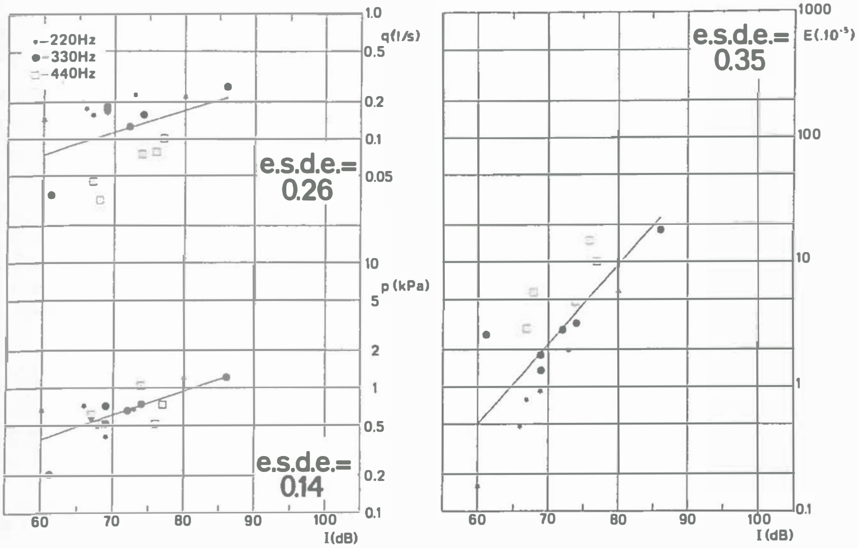


Figure 4-3. Depiction of the experimental data and regression lines for flow, pressure, and efficiency from Subject No. 32. Regression lines for the complete measuring series have been represented. A high value has been found for the e.s.d.e. for the efficiency, see text.

0.06 (Subject No. 50) to 0.27 (Subject No. 12), averaging 0.13.

For the pressure the e.s.d.e. varies from 0.06 (Subjects Nos. 8 and 50) to 0.23 (Subject No. 62), averaging 0.12.

For the efficiency, the e.s.d.e. diverges from 0.07 (Subject No. 50) to 0.35 (Subject No. 32), averaging 0.18.

In Subject No. 32 (e.s.d.e. = 0.26) and in Subject No. 11 (e.s.d.e. = 0.24), great dispersions in the flow data were measured. The experimental data and the regression lines of both subjects are represented in Figure 4-2 and Figure 4-3 respectively, where the frequencies at which the experimental data have been determined are indicated.

In Subject No. 11 it is obvious that the flow values measured at 220 Hz lie rather far from the regression line, and the measured values for the flow at 330 Hz nearly all lie under the regression line. For the efficiency, the experimental data at 220 Hz and 330 Hz nearly all lie above the

regression line. This is partly caused by the fact that the 330 Hz phonations were produced at a lower subglottic pressure than the other phonations at a comparable intensity value.
A possible explanation for this may be that at 330 Hz a resonance effect of the total vocal tract, together with mouthpiece, fluid-receptacle, and flowhead has played a role. The required intensity values might then be achieved at a lower subglottic pressure. House (1959) and Isshiki (1964) pointed out this possibility for certain pitches. However, in other subjects a systematic preference for values around 330 Hz could not be observed.
Another possibility may be that at a lower frequency a more efficient voice production results. However, in Subject No. 32 (Figure 4-3), it appeared that the phonations at 440 Hz were more efficient.

In the Figures 4-2 and 4-3, the data have been recorded for the highest values which have been calculated for the e.s.d.e. In these cases the residual spread seems to depend on the difference in pitch. It was not possible, though, to determine any relationship in this respect.

In cases in which the e.s.d.e. values approximated the average value, as in Figure 4-1, the experimental data at various pitches lie close to each other. (See in Figure 4-2 and Figure 4-3 the dispersion around the regression line for pressure.)

In cases of a very small residual spread (in Subject No. 50, e.s.d.e. = 0.06), as reproduced in Figure 4-4, further analysis of the relation to pitch has of course hardly any significance.

From data of trained voices of Singers (Nos. 3, 13, 17, 62, and 63) it appeared, that the residual spread in such cases is not much different from the average value, and the spread of the experimental data around the regression line of the efficiency is not noticeably better than in other subjects (see Table 4-3 Appendix). In Subject No. 62 only is the residual spread of the flow values notably lower than that of the pressure values.

We conclude that the pitch has little influence on the course of the regression lines. Therefore it is possible to characterize the voice production per measuring series sufficiently by using one regression line only for flow,

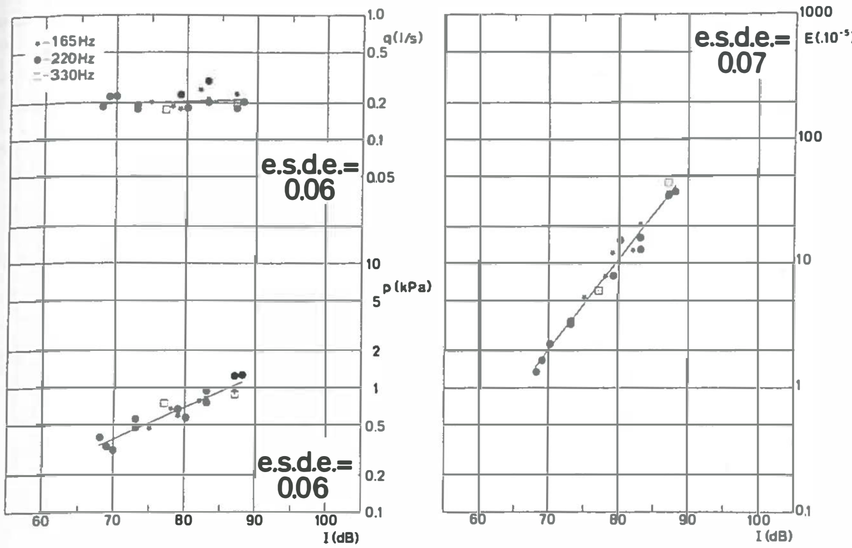


Figure 4-4. Depiction of the experimental data and regression lines for flow, pressure, and efficiency from Subject No. 50. The regression lines for the first complete measuring series have been represented. For flow, pressure, and efficiency, low values have been found for the e.s.d.e. Differentiation of the experimental data according to pitch hardly has any significance.

pressure, and efficiency, respectively.

4.3.3 Regression lines of measuring series from one subject at different times

In 12 male Subjects (Nos. 1, 2, 3, 8, 12, 13, 16, 17, 18, 35, 61, and 62) and 8 female Subjects (Nos. 9, 10, 26, 27, 28, 30, 49, and 50) more than one series was carried out. In two male Subjects (Nos. 1 and 62) measuring series were taken three times and in one male Subject (No. 2) seven times.

For every measuring series the values for flow, pressure, and efficiency have been calculated at the same intensity i.e. at the average of the midrange intensity values ($\bar{I}_m$) of the separate measuring series. In this way the behaviour of the same larynx at various days was always compared

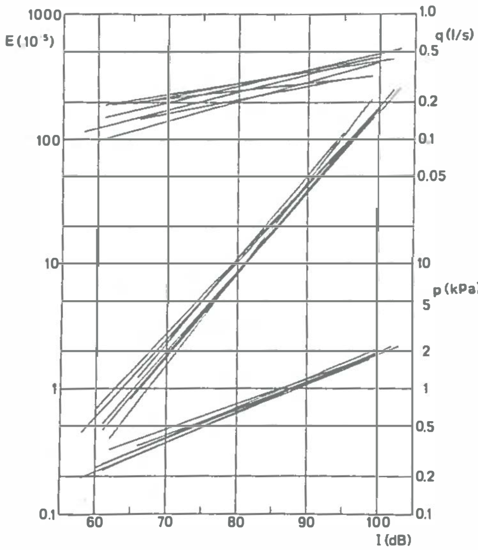


Figure 4-5.
Depiction of the regression lines for seven measuring series from the male Subject without voice training, No. 2. Between the first and the last measuring series, about four years elapsed. It is obvious that the differences are small, especially those for the subglottic pressure. The flow values show greater differences.

at the same intensity value.

It appeared that in most cases the differences in the course of the regression lines of different measuring series of the same subject were small.
If, moreover, the dispersion of the individual data is taken into account also, it may be asserted that there is a good reproducibility.

This can be illustrated with the aid of the experimental data from Subject No. 2, who has been examined seven times (Figure 4-5) and two more Subjects, No. 10 (Figure 4-6) and No. 61 (Figure 4-7). These three subjects had no vocal training. Between the two measuring series of Subject No. 61 one month and in the case of Subject No. 10, indeed, 22 months elapsed.

It naturally is not feasible to represent graphically all the results with respect to the reproducibility. The data are given in Table 4-4 (Appendix).

4.3.3.1 Discussion on the results

In evaluating the results when more than two measuring series were obtained from the same subject, we have used the differences between two successive measuring series.

Air flow rate

The greatest difference for the flow is 135 ml/s, determined between the two measuring series in Subject No. 12. The remaining dif-

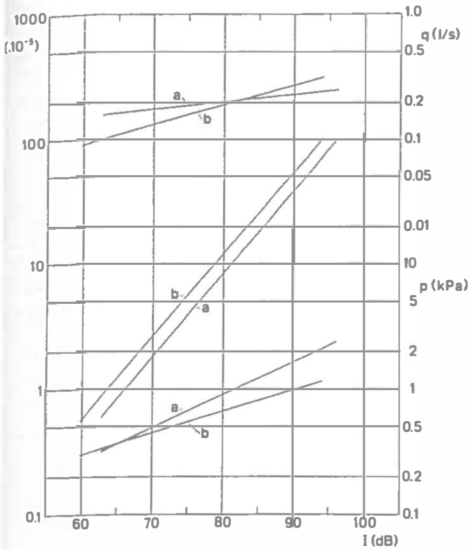


Figure 4-6.
Depiction of the regression lines for both measuring series from the male Subject without voice training, No. 10. Two years elapsed between the two series. The difference in slopes of the regression lines for pressure are nearly the highest slope differences established in the measurements of reproducibility. In the first measuring series, the value for the slope of the flow regression line is small and for pressure large, whereas in the second measuring series, the reverse is the case. Therefore, the regression lines for efficiency run parallel.

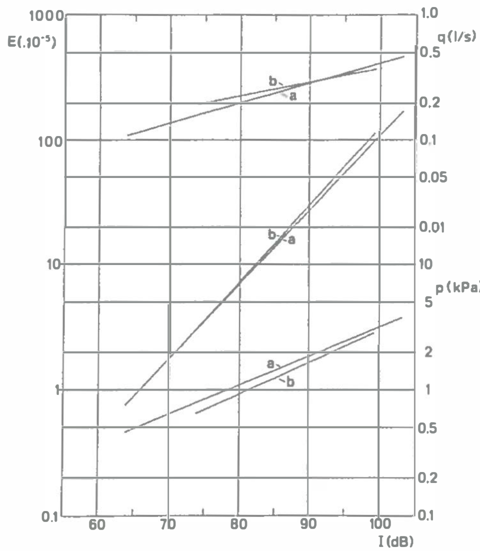


Figure 4-7.
Depiction of the regression lines for the two measuring series from the male Subject without voice training, No. 61. One month elapsed between the two measuring series. A good reproducibility exists between the measuring series.

ferences are much smaller and all lie below 90 ml/s, averaging 32.5 ml/s.

Naturally, the values for the slope of the regression line also show variations. The difference in the value of the regression coefficient b is in one case only more than 0.01 (Subject No. 26). The average difference amounts to 0.005.

Subglottic pressure

In 17 out of 27 assessed combinations the difference between pressures appeared to be smaller or equal to twice the error of measuring (i.e. 0.1 kPa, 1 cmH_2O). The greatest deviation has been observed in Subject No. 13, 0.34 kPa (3.4 cmH_2O). This fairly large difference may possibly be the consequence of the fact that in the first measuring series from this singer only high sound intensities were used.

The slope of the regression lines also appears to differ little. The absolute deviations in the data, as represented for the regression coefficient b in Table 4-4, are nowhere larger than 0.01. What a difference of about 0.01 in b actually signifies can be read from Figure 4-6, Subject No. 10, in which the regression lines for pressure have a difference for the slopes of 0.009.

On an average, the differences in the values for b are much lower, about 0.003. This difference is present in Figure 4-7 (Subject No. 61), as the difference of the slopes of the regression lines for the efficiency.

Efficiency

For the efficiency it holds that, due to the steep course of the regression line, a small change of the slope may lead to a rather considerable difference in the values at I_m.

The variations of the efficiency values were greater than those of the flow and pressure. The average difference amounted to 1.9×10^{-5}, the largest difference was found in Subject No. 28, 8.7×10^{-5}.

As far as differences in the slopes are concerned, in this respect, some high values were observed (in the Subjects Nos. 1, 28, and 49 respectively values of 0.015, 0.02, and 0.016). The average difference though is hardly any greater than the one observed for flow and pressure, viz 0.006.

The differences in the values of E_{rel} (see Chapter 3) expressed in decibel appear to vary between 0 and 3.4 dB. This last value has been observed in Subject No. 12.

4.3.3.2 Significance of E_{rel} for the comparison of regression lines

With the relative efficiency measure E_{rel}, expressed in decibel, it is possible to indicate the efficiency of voice production in each single case (see 3.6).

The value E_{rel} is subject to incidental variations. The degree in which this occurs in measuring series at different times from the same subject determines which change of E_{rel} in patients is significant.

The variance of the incidental variations of E_{rel} in normal subjects who have been examined more than once, see Table 4-3, has been estimated from pooled variances of these subjects.

$$\hat{\sigma}^2 = \frac{\Sigma(n_i-1) \times s_i^2}{\Sigma(n_i-1)} \qquad (4\text{-}1)$$

n_i = number of observations in the i-st person

s_i = standard deviation in the i-st person

Herewith has been assumed that the variances for all persons are identical.

Calculation yields

$\hat{\sigma}^2 = 0.65$ ($\hat{\sigma} = 0.81$).

In comparing the measuring series in patients the differences in E_{rel}, ΔE_{rel} are made use of. The variance of the difference of two independent quantities, in our case ΔE_{rel}, equals the sum of their variances.

The variance of the difference between two measuring series, i.e. of E_{rel}, is thus estimated as

$\hat{\sigma}_v^2 = 2 \times \hat{\sigma}^2 = 1.30$; ($\hat{\sigma}_v = 1.14$).

By assuming that the difference between two measuring series is normally distributed with zero expectancy and a standard deviation σ_v, estimated at $\hat{\sigma}_v = 1.14$ (at 27 degrees of freedom), the interval of ΔE_{rel} with the chance $1-\alpha$, the probability range, is

$$\left(-t_{1-\frac{\alpha}{2}} \times \hat{\sigma}_v \; ; \; t_{1-\frac{\alpha}{2}} \times \hat{\sigma}_v\right) \qquad (4\text{-}2)$$

Here, $t_{1-\frac{\alpha}{2}}$ is the $1-\frac{\alpha}{2}$ st fraction of the t-distribution with 27 degrees of freedom. For $1-\alpha = 0.10$, we find $t_{0.95} = 1.703$: the interval is (-1.94; 1.94).

This means that it may be considered a significant change between measuring series with an unreliability threshold of 10% if the difference $/\Delta E_{rel}/$ is larger than 2 dB.

4.3.4 Summary, intra-individual and inter-individual differences

The differences between the regression lines of the measuring series of one single subject at various times appear in general not to be great.

It is obvious that these differences will be much smaller than those occurring between various subjects. Compare e.g. in Table 4-3 the differences between flow data from Subject No. 12 (about 300 ml/s), Subject No. 30 (about 75 ml/s), or Subject No. 49 (about 115 ml/s).

The differences in pressure and efficiency also appear to be greater between the instances of phonation of various individuals than those measured in one single subject. This accentuated the good reproducibility of the measurements.

The good reproducibility is also illustrated e.g. by the remarkably low flow values from Subject No. 30. In a second measuring series after five months, practically the same experimental data were obtained. These low flow values consequently go along with a remarkably high efficiency, which was the same for both measuring series (see Table 4-3).

In Subject No. 27, in the first measuring series a remarkable course of the regression line for flow was observed. Contrary to almost all other measuring series, the flow decreases at increasing sound intensity (see the negative values for the regression coefficient b in Table 4-3). Moreover, it will be noticed that the pressure rises only very gradually (b deviates only very little from zero) at increasing intensity. At the second measuring series, after 2 months, practically identical results were obtained. This fact, too, speaks in favour of a good reproducibility.

Seidner, Wendler, and Stürzebecher (1975) reported extensively on the great inter-individual spread in the data from several normal subjects, making the determination of normal values very difficult. The dispersion of flow data at accurately defined pitches and intensities appeared to be 2 to 3 times smaller in a single subject than between subjects (Seidner and Stürzebecher, 1978).

The dispersion described by Seidner et al. - expressed in the variation coefficients - corresponds with the values described in 4.3.1.

For all male subjects the reproducibility of the efficiency appears to be very good. In female subjects the variations are somewhat larger in general. This is mainly the result of differences in flow values. The smallest variations were observed in the pressure values.

4.4 The set of all regression lines of the normal subjects: reference areas

4.4.1 Introduction

The regression lines of the series from all normal subjects form three bundles of lines: flow, pressure, and efficiency. Due to their divergent courses, these bundles each cover a certain territory called its reference area. Some of these lines will be discussed separately, because they form the limits of the reference area. The established reference areas will be discussed in 4.4.3.

In 4.2 has been mentioned already that a fairly large number of the measured phonations were rejected by trained listeners. Regression lines based upon these rejected phonations are compared with the reference areas in 4.4.4.

4.4.2 The set of all regression lines

If the regression lines from various subjects are represented together, making mutual comparison possible, there appear to exist considerable differences. Figure 4-8 provides a clear picture of these diverging values.

The regression lines from the male and female subjects have been represented together, as they cover nearly identical areas in both men and women. Moreover, there is no significant difference if only the regression line from the first measuring series or those from all series are used. This could be expected, because the intra-individual variation is smaller than the inter-individual variation.

The regression lines for air flow rate, subglottic pressure as well as for efficiency occupy a large area. This shows how large the inter-individual differences are. Regression lines at the borders of the bundles have been given a subject-number, to indicate their origin. These regression lines will be discussed separately.

Air flow rate

The regression lines for the flow diverge very much: e.g. at 70 dB the flow varies from less than 50 ml/s to about 300 ml/s. The lower border of the reference area is formed by both regression lines from Subject No. 30. Low flow values also have been measured in Subject No. 28. The regression lines in these subjects lie mainly below 100 ml/s.

The range of the air flow rate data at a moderate intensity is in general 100 ml/s to 300 ml/s, but larger differences occur at the ultimate values of the intensity ranges.

In some normal subjects the relation between flow and intensity is very weak, which also appears from the fact that the regression coefficient b in Table 4-3 is almost zero.

The highest value for b has been determined in Subject No. 44; this regression line lies at the upper limit of the bundle at 80 dB. Up to an intensity of 75 dB the regression lines from the Subjects Nos. 5 and 12 form the upper limit. Above 95 dB the limits are determined by the regression lines from the Subjects Nos. 3, 18, 19, 27, and 53.

Subglottic pressure

The regression lines for the pressure appear to occupy a smaller area than those for the flow. The inter-individual differences are smaller.

The intra-individual differences are also smaller than those for the flow.

The increase in subglottic pressure connected with an increase in sound intensity appeared to be practically the same in most of the subjects (virtual equal values of the regression coefficient b).

One of the regression lines of Subject No. 27 shows a course which deviates from the other lines; it takes a nearly horizontal level. Because of the great dynamic range this regression line runs at the upper border at low sound intensities and at the lower border at high sound intensities.

The lower limit of the bundle of lines is determined furthermore by the regression line from Subject No. 12. The flow regression line of one of the measuring series of the same person lies at the upper border of the bundle of lines. However, both lines are not derived from the same measuring series. The border line with low subglottic pressure values, indicated as 12b, is not accompanied by a regression line with high flow values. The flow regression line corresponding with 12b lies in the middle of the bundle of lines for flow. The high regression flow line 12a though is accompanied by rather low pressure values, see Figure 4-8.

At high sound intensities (above about 90 dB) very high subglottic pressures in singers (tenors) were measured. The regression lines show

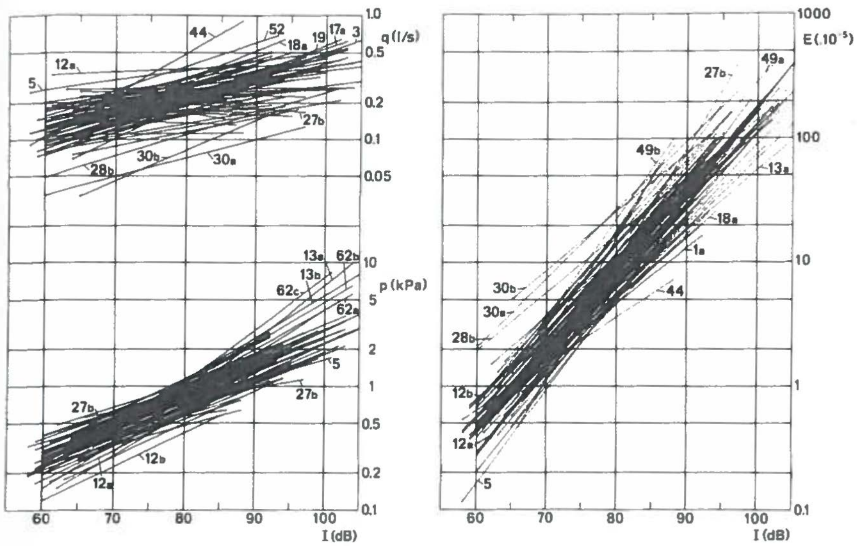


Figure 4-8. The set of all regression lines from the phonations with non-deviant sound quality. The regression lines from 72 measuring series in 45 normal subjects have been represented. The numbers indicate the subjects, the indices a, b, and c designate different measuring series in the same subject.

values which surpass a value well above 5 kPa (50 cmH_2O). Such high values practically only occur in the singers in our investigation. In all remaining subjects, including those who also could produce a sound intensity of 105 dB, the subglottic pressure remains less than about 3.5 kPa (35 cmH_2O). Both Tenors (Nos. 13 and 62) will be discussed in Chapter 6.

Efficiency

The spread of the regression lines for the efficiency is smaller than the spread in the air flow rate, but larger than that of the subglottic pressure. This could be the result of a compensating effect (high values for flow at low subglottic pressures and vice versa). This effect had been previously observed in Subject No. 8 (see 4.3.1). In Subject No. 12a, the high values for flow coincide

with low values for subglottic pressure.
This means that the efficiency regression line runs through the centre of the reference area. Such a compensating effect, though could only occasionally be observed.

The low flow values from Subject No. 30 result in a high efficiency. The efficiency regression lines (together with those from Subject No. 28) define the upper border of the bundle of lines for efficiency, while the regression lines for pressure on the other hand lie in the middle of their bundle.

At the lower side run the efficiency regression lines from Subjects Nos. 5 and 44; the high flow values in these cases have not been compensated by low pressure values.

Above 85 dB, by a favourable combination of flow and pressure values the regression line from Subject No. 49 is situated at the upper side of the bundle.

The steep slope of the efficiency regression lines from Subject No. 27 is the result of the horizontal course of the regression line for pressure and the decrease of the flow at increasing intensity. By this combination, this Subject delimits the efficiency bundle at the intensity top side, i.e. above 90 dB.

At high intensities, the regression lines from the singers appear to lie in the lower part of the bundle of lines.

4.4.3 Reference areas for flow, subglottic pressure, and efficiency

From the broadness of the bundles of regression lines, it is obvious that it is not possible to provide precisely circumscribed "normal values" for flow, pressure, or efficiency.

The subjects in our experiments, as opposed to the patients observed, never had vocal disturbances, their larynxes showed no abnormalities, and the produced sounds were not audibly deviant. Their regression lines thus show which variations may occur in "normal" phonations of subjects. The large spread of the regression lines from the normal subjects, interferes with an assessment of abnormality of a regression line from a patient.

Reference areas

The reference areas for flow, pressure, and efficiency have been

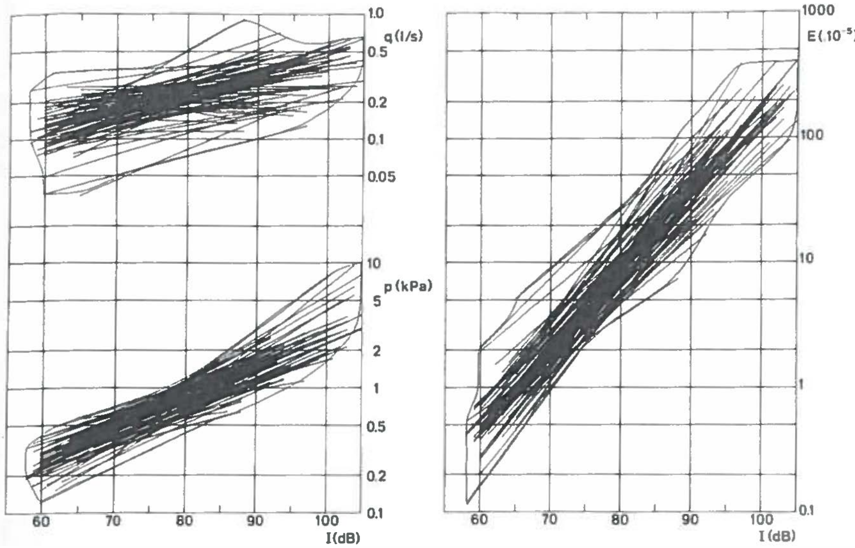


Figure 4-9. Delimitation of the reference areas. Contour lines around the regression lines indicate the limits of the reference areas.

determined by drawing contour lines around the respective bundle of lines. These contour lines have been drawn in such a way that all regression lines are encircled, see Figure 4-9.

4.4.4 Rejected phonations in relation to the reference areas

In 4.2 has been mentioned that a fairly large number of phonations from normal subjects have been rejected by experienced listeners. This amounts to 1531 from a total of 4267 instances of phonation.

The rejected phonations were mainly produced at pitches and/or sound intensities at the limits of the vocal potentialities. The pertinent phonation then lies at the border of the phonetogram (see 2.2.1.2). Moreover, for certain subjects the pre-selected frequencies were either too low or too high. For these subjects, it was still possible to phonate following the given pitch, but the quality of the voice was not satisfactory and soft phonations often appeared to be breathy.

At pitches in the neighbourhood of the register transition from chest voice to falsetto voice, a number of mainly soft phonations have been assessed as deviant and were rejected.

Finally, a phonation occasionally seems to have a deviant sound quality whereas the successive phonation, following this one and sung at the same pitch and intensity, seems altogether normal in sound quality. This is due, of course, to the possibilities of varying the sound quality. A deviant phonation ensues when the attention of the subject slackens. Occasionally a reminder results in a favourable effect, but giving instructions on the quality of the voice ought to be avoided as much as possible. Sometimes a critical remark leads to confusion.

We studied the course of the regression lines of 21 discarded measuring series with respect to the reference areas, see Figure 4-10.

The 21 regression lines comprised 817 phonations. The other rejected phonations (714) originated from the 45 normal subjects in Table 4-1. If these 714 phonations are included in the calculation of the relevant regression lines, it appears that the course of these lines is only very little influenced.

Air flow rate

It appears that only two flow regression lines of discarded series run outside the reference area, the remaining ones all lie within the flow reference area. Most of these discarded regression lines, though lie in the upper part of the reference area. This actually means however, that hoarse or breathy phonations are possible with the same air flow rates as normal sounding phonations.

Two other discarded flow regression lines running approximately through the middle of the flow reference area, originate from the same subject. These phonations were regarded by the listeners as strained.

Subglottic pressure

The pressure regression lines of the deviant phonations lie in the upper part or just outside the pressure reference area.

Two of the pressure regression lines, which go on to 100 dB resp. 105 dB, originate from the same person. This is the same subject

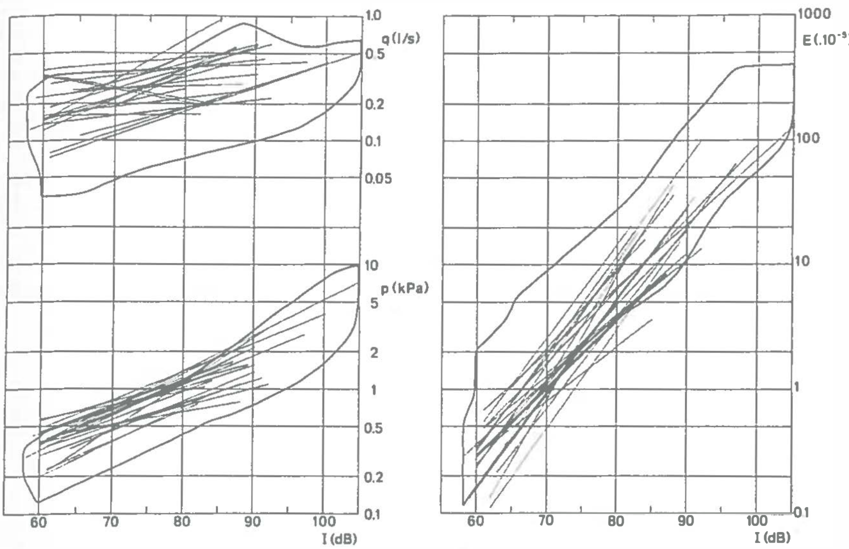


Figure 4-10. Depiction of the regression lines from rejected measuring series. The relevant phonations have been rejected as a result of the judgement of listeners who found the vocal sound to be deviant. The majority of the regression lines lies within the reference areas. From an aerodynamic point of view, the deviant phonations are distinguished from phonations with non-deviant sound quality to a minor degree only.

mentioned already, whose phonations have been judged as strained. It is remarkable that above 90 dB his pressure regression line goes up to values which are otherwise only observed in two Singers (Nos. 13 and 62).

Efficiency

As could be expected most efficiency regression lines for the discarded phonations lie in the lower part of the efficiency reference area, and some just outside it. So most of the discarded phonations are less efficient than those that were accepted. Due to the combination of pressure and flow the efficiency regression lines deviate the most.

In summary, it may be stated that the influence on the reference areas of eventual deviating phonations which escaped rejection is not great. This is of course related to the inter-individual differences. The aerodynamic data of a deviant phonation from one person may thus lie close to the data of a good phonation from another person.

This means also that a deviant value may still lie within the reference area, even though it is considerably different from the normal values of the same subject.

4.5 Published data concerning 'normal values' compared with data determined in this investigation

We found in the literature only three investigations of simultaneous measurements of air flow rate, subglottic pressure, intensity, and pitch. In published results of other investigations the great degree of inter-individual variation does not become apparent because simultaneous measurements were carried out in these on only relatively few subjects. Most studies comprising measurements on a great number of subjects report the mean air flow rate only.

Comparison of our data with data from the literature is, moreover, difficult, because in many cases neither intensity nor pitch have been reported. In many publications too, only mean values and, in some cases, a measure of variation have been mentioned.

In order to evaluate experimental data from a patient, the range of the experimental data from normal subjects is of greater importance than the mean values. Koike and Hirano (1968) stress this fact emphatically and they handle the statistical concept "critical region".

4.5.1 Data for the air flow rate

4.5.1.1 Range and mean value

For flow measurements various methods were used. Table 4-5 gives a survey of investigations based on at least ten subjects reporting air flow rates compared with our own study. A subdivision is made for each of the different methods.

The measuring procedures are divided by us in seven subgroups according to the method for establishing the air flow rate:--

I. By dividing the Vital Capacity (VC), beforehand obtained with a spirometer, by the maximum phonation time of a maximally sustained phonation (the Phonation

Quotient, PQ), as in the studies by Hirano, Koike, and von Leden (1968), Bastian, Sasama, and Unger (1978), and Sawashima, Yoshioka, Honda et al. (1978).

II. By derivation from the volume curve, obtained with either a spirometer (mfr) or a bag, as in the studies by Roudet (1900a), Gutzmann and Loewy (1920), Schilling (1925), Döhne (1944), van den Berg (1956), Kunze (1962), Ptacek and Sander (1963a, b), and Sawashima, Yoshioka, Honda et al. (1978), or with a bodyplethysmograph, as in the studies by Bouhuys, Proctor, and Mead (1966).

III. By dividing the total volume curve of expired air during phonation, obtained with a spirometer, by the maximum phonation time after maximum inspiration (MFR), as in the studies by Isshiki, Okamura, and Morimoto (1967), and Sawashima, Yoshioka, Honda et al. (1978).

IV. By dividing the total volume curve, obtained by integration of the pneumotachograph signal during maximally sustained phonation, after maximum inspiration (the Phonation Volume), by the phonation time, as in the studies by Isshiki (1964, 1965), Yanagihara, Koike, and von Leden (1966), Isshiki, Okamura, and Morimoto (1967), Yanagihara and Koike (1967), Yanagihara and von Leden (1967), Hirano, Koike, and von Leden (1968), Koike and Hirano (1968), Iwata and von Leden (1970a, b), Iwata, von Leden, and Williams (1972), Kelman, Gordon, Simpson et al. (1975), Bastian, Sasama, and Unger (1978), Gordon (1978), Gordon, Morton, and Simpson (1978), and Hippel and Mrowinski (1978).

V. By dividing the volume curve, obtained by integration of the pneumotachograph signal, by the phonation time, as in the studies by Isshiki (1964), Isshiki and von Leden (1964), and von Leden (1968).

VI. By direct reading from the pneumotachograph curve, averaging over an interval of some seconds (2-5 s), as in the studies by Isshiki and von Leden (1964), Vaughn (1965), Isshiki, Okamura, and Morimoto (1967), McGlone and Shipp (1971), Shipp and McGlone (1971), Stürzebecher, Seidner, Wagner, et al. (1973), Seidner, Wendler, and Stürzebecher (1975), and Seidner and Stürzebecher (1978).

VII. By direct reading from the pneumotachograph curve, as in the studies by Luchsinger (1951), Vogelsänger (1954), Cavagna and Margaria (1965, 1968), Rubin,

Table 4-5. A survey of data from the literature concerning the range, the average value, and the dispersion of the experimental data for flow in sustained phonations together with the number of investigated subjects (males and females). The conditions of the experiments are given in the last column. The Roman numbers indicate the measuring procedure, see text.

name of first author		number of testpers.	range ml/s	mean ml/s	S.D.	conditions
I. Hirano	(1968)[1]	25 m	69 - 307[2]	145	--	comf.pitch and int.
		25 f	78 - 241[2]	137	--	
Sawashima	(1978)	25 m	56 - 205[2]	130	34.6	comf.pitch and int.
		25 f	23 - 230[2]	126	47.9	
Bastian	(1978)	51 f	--	200	100	sel.int. and comf.pitch
II. Kunze	(1962)	10 m	73 - 284[3]	160	20	sel.pitch and int.
Sawashima	(1978)	25 m	66 - 162	112	23.0	comf.pitch
		25 f	38 - 140	89	23.7	
III. Isshiki	(1967)	5 m	94.7- 153	123.1	19.5	comf.pitch and int.
		5 f	68.7- 162	133.0	33.0	
		10 m+f	68.7- 162	127.9	27.0	
Sawashima	(1978)	25 m	45 - 147	96	23.7	comf.pitch and int.
		25 f	13 - 181	97	39.1	
IV. Yanagihara	(1966)	11 m	55 - 310	112	30.4	comf.pitch and int.
		11 f	55 - 310	100	22.8	
Yanagihara	(1967)	11 m	--	153	56.2	high pitch
		11 f	--	149	37.8	
		11 m	--	118	30.4	medium pitch
		11 f	--	100	22.8	
		11 m	--	114	39.5	low pitch
		11 f	--	95	37.4	all with comf.int.
Isshiki	(1967)	5 m	104.7- 164.3	126.2	21.1	comf.pitch and int.
		5 f	69.0- 171.0	135.9	36.4	
		10 m+f	69.0- 171.0	131.1	30.5	

table 4-5

name of first author		number of testpers.	range ml/s	mean ml/s	S.D.	conditions
cont. IV						
Hirano	(1968)	25 m	46 - 222[2]	101	--	comf.pitch and int.
		25 f	43 - 197[2]	92	--	
Koike	(1968)	21 m	--	112.4	36.2[4]	comf.pitch, medium
		21 f	--	93.7	31.6[4]	loudness
Iwata	(1972)	see Hirano (1968)				
Kelman	(1975)	28 m+f	80 - 200[3]	--	--	comf.pitch and int.+ highest and lowest pitch in chest register
Hippel	(1978)	19 m+f	190 - 300[3]	--	--	comf.pitch, 3 sel.int.
Bastian	(1978)	51 f	--	151	62	sel.pitch and comf. pitch
V.Isshiki	(1964)	- m	62 - 360	141	22.5	extremes in pitch and
		- f	44 - 315	119	25.0	int. included
		36 m+f	76 - 182	130	26.0	comf.pitch and int.
Vaughn	(1965)	20 m	175 - 250[3]	--	--	4 sel. pitches, int. range 6 dB
Isshiki	(1967)	5 m	not different from the			
		5 f	values given in group III			
VI.Shipp	(1971)	14 m	--	177[3]	30.4[3]	at 25% int.level various pitches
Seidner	(1975)	37 m	237 - 4B2	--	--	2 pitches
		63 f	195 - 441	--	--	int.range 10 dB
VII.Luchsinger	(1951)	20 m+f	41 - 216	--	--	various pitches
Vogelsänger	(1954)[1]	29 m+f	40 - 300	--	--	various pitches, flow range determined at 70 dB (see Figure 4-11)
Schutte	this[1]	24 m	105 - 350	181	--	various pitches
	monograph	21 f	45 - 300	132	--	flow range determined at
		45 m+f	45 - 350	160	74[4]	70 dB (see Figure 4-9)

[1] transformed values were used for calculation

[2] calculated critical region 95%

[3] not explicitly given, derived from published figures or tables

[4] the difference between the flow rate values at 70 dB for the transformed mean $\bar{x}$, and for transformed $(\bar{x} + s)$ in ml/sec.

LeCover, and Vennard (1967), Cavagna and Camporesi (1974), Schutte and van den Berg (1976), and this monograph.

Luchsinger (1951) was the first to use a pneumotachograph for measuring flow in phonation. He examined 20 singers.

At the same sound intensity, flow values between 41 ml/s and 216 ml/s were measured for various pitches. Such divergent values were explained by him as consequences of inter-individual differences in the structure of the larynx.

Vogelsänger (1954) registered the flow in 29 singers for two intensities at various pitches. In his publication, the data for flow together with the data for intensity have been presented for 960 phonations.
Though exact comparison of the sound intensities is not possible (difference in the distance to the microphone etc.), the experimental data per subject were converted by us to regression lines. These regression lines are represented in Figure 4-11. They cover practically the same area as the reference area determined by us for flow.

Kunze (1962) concluded that the relation between flow and intensity shows rather large inter-individual differences.

Isshiki and von Leden (1964) introduced the idea of allowing the subjects to phonate at a comfortable pitch and intensity of their own choice.

In all investigations following their principle of "easy and comfortable phonation", the flow ranges appear to be smaller than those implied by our reference area (Figure 4-9).

Isshiki and von Leden (1964) give for the air flow rate at "easy phonation" a range of 76 ml/s to 182 ml/s. If the phonations with "extreme variations in pitch and intensity" are included, the ranges are 62 ml/s to 360 ml/s for males and 44 ml/s to 315 ml/s for females. The intensity ranges were not mentioned. The limits given by these authors for the extremes of pitch and intensity do not differ much from the limits of our reference area.

Hirano, Koike, and von Leden (1968), Koike and Hirano (1968), and Iwata, von Leden, and Williams (1972) use the statistical concept of "critical region" for the description of normal value limits. For this purpose they start from the mean values for males and females and arrive at different limits for males and females. Hirano, Koike, and von Leden (1968) assert, "The critical region indicates that a mean flow rate of less than 46 cc/s in a male or 43 cc/s in a female or a mean flow rate greater than 222 cc/s in a male or 197 cc/s in a female should be regarded as abnormal."

Compared with our reference area (Figure 4-9) the published "normal values" are slightly smaller. This may be due to the procedure used by other authors. At a free choice of pitch and intensity in most of the reported experiments the subjects were asked to phonate after a maximal inspiration. In some cases, the longest phonation of a number of phonations has been taken as the "normal value" (Hirano, Koike, and von Leden, 1968; Hirano, 1975; Sawashima, Yoshioka, Honda et al., 1978). Moreover, the subjects in these investigations were given careful instructions and often beforehand got an opportunity to get familiar with the required phonatory task. It may be assumed that the consumption of air in this procedure would be less than in our method.

Sawashima, Yoshioka, Honda et al. (1978) investigated the influence of the phonatory task on the flow value. They conclude that measuring of the smallest flow values for easy phonation after normal breathing should be preferred in examining and recording the every day use of the vocal apparatus. Moreover, by taking the smallest flow value Sawashima et al. obtained low mean values.

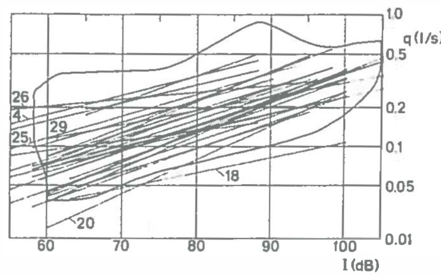


Figure 4-11.
Depiction of the regression lines for flow values obtained by evaluation (using the method described in Chapter 3) of the data from Vogelsänger's investigation. He considered 29 subjects, 25 singers and 4 patient-singers, Vogelsänger (1954). The regression lines mainly lie within the in 3.4.3 indicated reference area. The lines marked with 4, 25, 26, and 28, are from the patient-singers, using Vogelsängers numeration.

Cavagna and Margaria (1965) and

Cavagna and Camporesi (1974) explained the fact that a phonation with constant pitch and sound intensity may have considerably different flow rates. They established that a certain minimal flow was needed to keep the phonation going. The amount of the minimal flow is related to the sound intensity. With high speed motion-pictures of the vocal folds during phonation they found that flow values higher than the minimal flow values may be obtained by letting air pass via the posterior part of the glottis ("air shunting"). This part will then obviously be brought into incomplete adduction. The vibration of the vocal folds is often limited to the anterior part of the glottis.

The minimal flow has also been discussed by Luchsinger (1951), who defined the concept "Minimalluft", coined by the singing-teacher Paul Bruns, as "das möglichst kleine Luftquantum mit dem ein gut brauchbarer Ton in jeder Stimmlage und in jeder Tonhöhe erzeugt werden kann".

Vogelsänger (1954) also assumed that professional singers use less air than untrained people. In view of his own data, however, (see Figure 4-11), this is not the case, only two of the regression lines, from his Singers Nos. 18 and 20, partly lie under our reference area.

4.5.1.2 Reference regression line

All authors stress the fact that the mean flow value in women lies below that value in men. To be able to compare these mean values with our values we computed reference regression lines. These were determined from the average values of the regression coefficients b and a.

Table 4-6 gives the data for the air flow rates. The reference regression lines were computed for males and females separately and for both groups together.

A number of subjects had been examined more than once, a reference regression line also was computed then for their first measuring series and for all measuring series together.

It appeared that it makes little difference whether only the first measuring series of a subject or all measuring series together are used.

Table 4-6 shows that a remarkable difference between male and female values was also present in the mean values of the flow data measured

Table 4-6. Table of the regression coefficients of the flow reference regression line for various groups of normal subjects in this investigation. The calculated flow has been recorded for the intensity values 70 dB and 90 dB.

	measuring series	coefficient of regression $bx10^{-2}$	a	calculated flow in ml/s at 70 dB	90 dB	number of measuring series
males	first	1.290	1.353	180	326	24
	all	1.218	1.405	181	317	43
females	first	1.085	1.386	140	231	21
	all	1.049	1.388	132	215	29
males +	first	1.194	1.368	160	278	45
females	all	1.15	1.398	160	271	72

by us. Though most authors have described this phenomenon, no satisfactory explanation has been given so far.

We suggest that the fact that the consumption of air in phonation in women is smaller than in men may be connected with the fact that the female glottis is less in length and width. This is the consequence of the smaller anatomical structures, which also causes the higher speaking voice pitch level in women.

Our mean flow values at 70 dB - 132 ml/s for women and 181 ml/s for men - are for men somewhat higher, than the mean values found by other authors.

4.5.2 Data for the subglottic pressure

4.5.2.1 Range and mean value

Investigations on subglottic pressure in phonation have been performed by van den Berg (1956), Isshiki (1959), Kunze (1962, 1964), Ladefoged (1962), and Lieberman (1968). In these studies the number of subjects was small, but Loebell (1969) described direct pressure measurements in 100 subjects and 47 patients; however, he only gave an overall survey of experimental data.[1])

Van den Berg (1956) measured pressures in one subject (directly and indirectly) varying from 3.5 cmH_2O to 50.5 cmH_2O at a dynamic range of about 40 dB.

Isshiki (1959) and Perkins and Yanagihara (1968) registered the subglottic pressure by direct measurement, respectively in one and in two subjects, at various pitches and intensities. Their data correspond with those of van den Berg.

Kunze (1962), in ten male subjects, using a direct method (puncture of the trachea), found subglottic values during phonation ranging from 2.75 cmH_2O to 24.84 cmH_2O.

For every pitch and intensity, Kunze took the average of three measurements. He measured at five pitches, divided proportionally over the individual voice frequency range. At every pitch the values of the subglottic pressure for five vocal intensities were determined.

Shipp and McGlone (1971) reported values of pressure and flow in 14 subjects for two sound intensities (25% and 75% of the intensity ranges) at various pitches. For every pitch they gave a mean value for the subglottic pressure. These mean values range from 4.B9 cmH_2O (S.D. = 0.5) to 12.77 cmH_2O (S.D. = 1.02).

As can be seen from Figure 4-9, we found subglottic pressure values varying from 0.15 kPa (1.5 cmH_2O) to 10 kPa (100 cmH_2O).

At moderate values of intensity, the subglottic pressure varied over a range of about three times the lowest value, due to the inter-individual variations.

At an intensity level of 70 dB, the subglottic pressure varied from 0.2 to 0.75 kPa (2 to 7.5 cmH_2O), at 90 dB from 0.75 to 3 kPa (7.5 to 30 cmH_2O).

Subglottic pressure values above 3.5 kPa (35 cmH_2O) were found mainly in trained tenor singers.

4.5.2.2 Reference regression line

From the mean values of the regression coefficients of the separate regression lines, a reference

[1]) Very recently we received from Prof. Dr. E. Loebell the dissertations of Nold (1967), Glatz (1970) and Schuck (1971) on direct subglottic pressure measurements in patients, and of Mendl (1970) on normal subjects.

Table 4-7. Table of the regression coefficients of the pressure reference regression line for various groups of normal subjects in this investigation. The calculated pressure has been recorded for the intensity values 70 dB and 90 dB.

	measuring series	coefficient of regression		calculated press. in kPa at		number of measuring series
		$bx10^{-2}$	a	70 dB	90 dB	
males	first	2.644	-2.220	0.43	1.45	24
	all	2.622	-2.198	0.43	1.45	43
females	first	2.333	-1.975	0.45	1.32	21
	all	2.323	-1.980	0.44	1.29	29
males +	first	2.496	-2.105	0.44	1.39	45
females	all	2.50	-2.110	0.44	1.38	72

regression line is calculated, the regression coefficients for various groups of subjects being given in Table 4-7.

It is obvious from the calculated mean subglottic pressure values for 70 dB and 90 dB that practically no differences were found between the various groups.

All authors agree that subglottic pressure during phonation is closely related to sound intensity.

For the subglottic pressure range, Loebell (1969) and other authors have reported pressures up to about 3.5 kPa (35 cmH_2O) in normal subjects.

Apart from certain exceptions, e.g. the tenor singers, our upper limit also appears to lie at about 3.5 kPa (35 cmH_2O).

4.5.3 Data for the efficiency

4.5.3.1 Range and mean value

In determining vocal efficiency it is necessary to know the air flow rate as well as the subglottic pressure of the same phonation. Therefore, the published data concerning this subject are limited.

Van den Berg (1956) calculated efficiency values for the phonation of the vowel /a/ at a dynamic range of about 40 dB, varying from

Table 4-8. Table of the regression coefficients of the efficiency reference regression line for various groups of normal subjects in this investigation. The calculated efficiency has been recorded for intensity values 70 dB and 90 dB.

	measuring series	coefficient of regression $b \times 10^{-2}$	a	calculated effic. in $\times 10^{-5}$ at 70 dB	90 dB	number of measuring series
males	first	6.066	-3.974	1.9	30.5	24
	all	6.159	-4.048	1.8	31.3	43
females	first	6.587	-4.252	2.3	47.5	21
	all	6.628	-4.248	2.5	51.1	29
males +	first	6.309	-4.104	2.1	37.5	45
females	all	6.348	-4.128	2.1	38.4	72

0.45×10^{-5} to 45×10^{-5}, depending on the sound intensity, the pitch, and the opening of the mouth.

Margaria and Cavagna (1959) and Cavagna and Margaria (1965, 1968) discussed the increase of efficiency at increasing sound intensity.

Isshiki (1964) obtained values of 3×10^{-5} to 140×10^{-5}, using a single subject.

Perkins and Yanagihara (1968) also investigated a single subject. The efficiency values, as derived from their figures by us, varied from about 5×10^{-5} to 65×10^{-5}. These values fall within in the reference area determined by us.

Moser and Kittel (1979) recently published results of investigations on efficiency in voice production. They determined air flow rate and subglottic pressure with the aid of a bodyplethysmographic method, and calculated the efficiency by a directly coupled computer. Their results correspond with van den Berg's data.

As can be seen from Figure 4-9, we found efficiency values varying from 0.12×10^{-5} to 400×10^{-5} for a sound intensity range of 47 dB.

At a given intensity value, the efficiency varied within a range of about 10 dB, due to the inter-

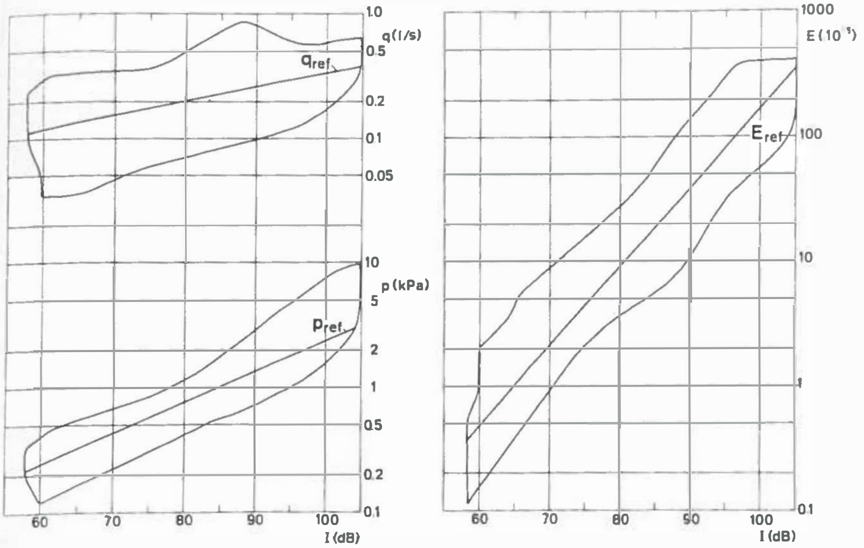


Figure 4-12. Depiction of the reference areas and reference regression lines for flow, pressure, and efficiency, ascertained on the basis of the 2736 non-deviant phonations, measured in this investigation in 72 measuring series in 45 normal subjects.

individual variations.

At an intensity level of 70 dB, the efficiency varied from 1×10^{-5} to 10×10^{-5}, at 90 dB from 10×10^{-5} to 110×10^{-5}.

4.5.3.2 Reference regression line

Mean values for the efficiency at 70 dB and 90 dB were calculated from the reference regression lines for various groups, see Table 4-8.

As expected the mean efficiency in women appears to be higher than in men. The difference between various groups of normal subjects again proved to be very small.

The reference regression lines based on all 72 measuring series in 45 normal subjects are represented, together with the reference areas, in Figure 4-12.

4.6 Normal and deviant sounding phonations from the same subject: intra-individual comparison

In previous sections the great inter-individual differences have been discussed, it was observed that the aerodynamic data of a deviant sounding phonation from one person may lie very close to those of a normal sounding phonation from another subject.

We shall now consider whether intra-individual differences between normal and deviant sounding phonations can be assessed. For this purpose we may compare the experimental data of intentionally hoarsely produced phonations with the regression lines and data from the same subject.

Certain normal subjects were asked during a measuring series to produce hoarse phonations. The curves from the hoarse phonations were elaborated in the usual way. Since the number of hoarse phonations was small, no computing of regression lines followed.

The aerodynamic differences between hoarse and "normal" phonations will be illustrated by a few examples.

Subject No. 2.

Subject No. 2 was asked, after a usual measuring series, to phonate in a very breathy manner (at E3, 165 Hz, about 75 dB).

The experimental data are indicated in Figure 4-13.

This figure also shows the regression lines of the seven measuring series with 344 non-deviant phonations.

The flow data from the four hoarse phonations can be distinguished clearly despite the dispersion of the experimental data around the regression lines. The flow data lie by a factor of about 3 above the other data at the same intensity.

The pressure data from the hoarse phonations, however, are found in the same area as those from the normal phonations.

The efficiencies of the hoarse phonations lie lower by a factor of about 3.

On the basis of Figure 4-13, the signification of phonation at phonetogram extremes, especially with regard to the flow data, can be illustrated. In the discussion of the rejected deviant phonations, we remarked (4.4.4) that these phonations often appeared to be

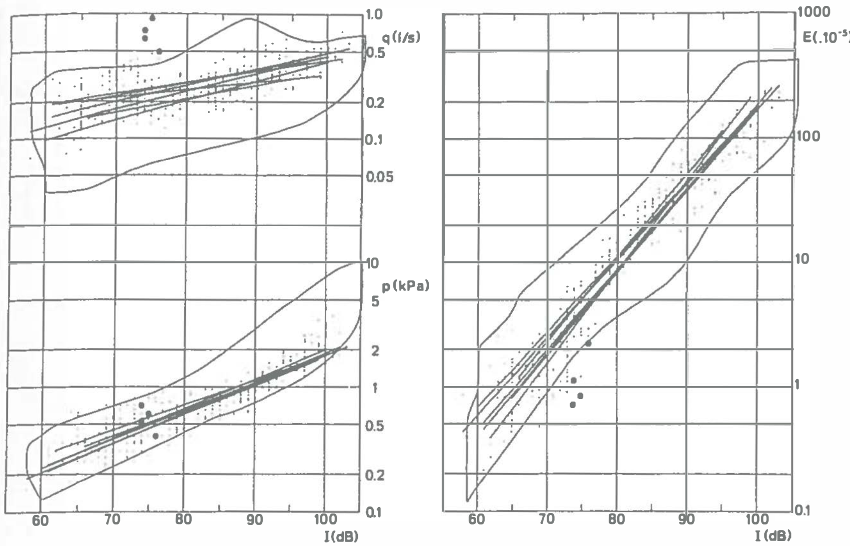


Figure 4-13. A comparison of experimental data from four phonations intentionally produced hoarse sounding and experimental data from a great number (344) of phonations with non-deviant sound quality in Subject No. 2. The experimental data from the hoarse phonations have been marked with a circle.

produced at the limits of the vocal potentialities.

In Subject No. 2, nearly all phonations below 75 dB with flow values above 300 ml/s originated from phonations at A2 (110 Hz).

From the phonetogram of this Subject (Figure 2-4) it may be seen that this pitch lies at the limit of his vocal range and that at this frequency there is only a very small dynamic range. At 110 Hz, a maximum sound intensity of no more than 70 dB could be reached. Loud phonations at extreme pitch levels lead easily to a high flow value and decreasing efficiency. Despite these high flow values, the phonations did not give the impression of being hoarse, but probably, nevertheless, lie in an area of transition to hoarse phonations. However, at 110 Hz, in some of the measuring series from Subject No. 2 no flow values exceeding 300 ml/s were found. This was the case, indeed in about half of the 60 phonations at

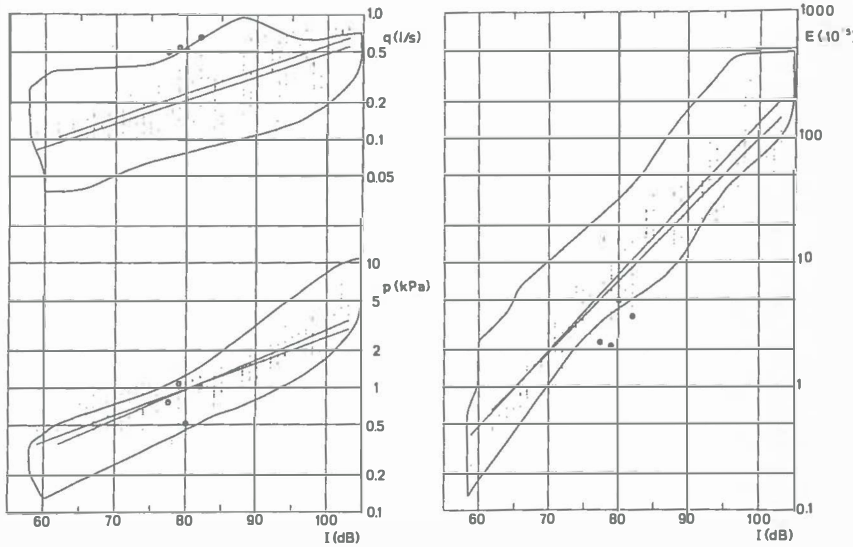


Figure 4-14. A comparison of experimental data from four phonations intentionally produced hoarse sounding and experimental data from phonations with non-deviant sound quality from both measuring series in Subject No. 17. The experimental data from the hoarse phonations have been marked with a circle.

110 Hz. In three measuring series, the flow values at 110 Hz lie definitely below 300 ml/s. Apparently the voice production at this extreme pitch level is more efficient some days more than others.

Subject No. 17.

In Figure 4-14, the experimental data from two measuring series in Subject No. 17 (Baritone) are given. At the end of a series, the subject was asked to produce a hoarse sound.

The data for flow, pressure, and efficiency in four hoarse phonations have been marked in Figure 4-14 in order to distinguish them from the data from normal phonations.

It is obvious that the hoarse phonations were characterized by high flow values, which distinguish them from normal sounding phonations.

The pressure data appeared not to be conspiciously different from

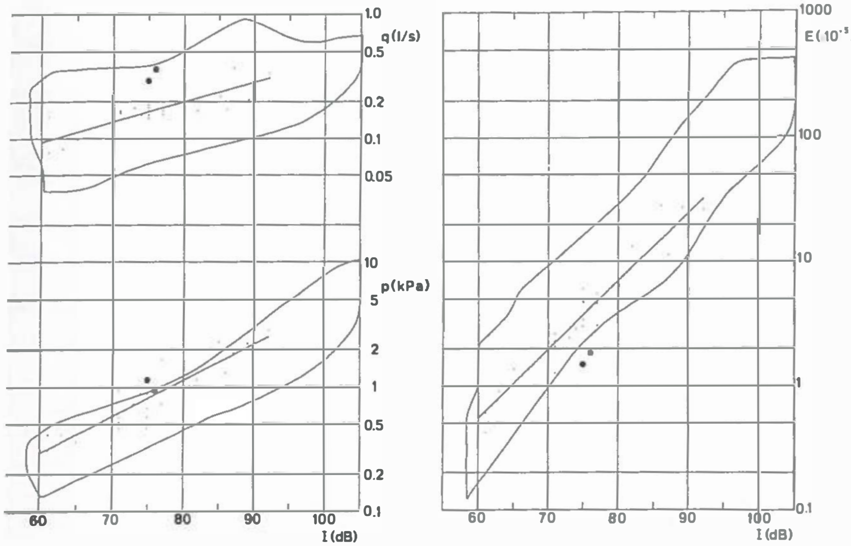


Figure 4-15. A comparison of experimental data from two phonations intentionally produced hoarse sounding and experimental data from phonations with non-deviant sound quality in Subject No. 60. The experimental data from the hoarse phonations have been marked with a circle.

those of normal phonations. The low subglottic pressure at 80 dB from this subject compensates for the high flow, causing the efficiency to lie near to the regression line derived from normal phonations. The remaining three efficiency values lie beneath those from normal phonations and outside the reference area.

Subject No. 60.

The flow data from the hoarse phonations, represented in Figure 4-15, lie evidently within the reference area. Compared with the flow values commonly used by this subject, the hoarse phonation flow values are higher by as much as a factor 2 and can be clearly distinguished from the normal values.

The subglottic pressures in the hoarse phonations were found outside the pressure reference area. However, as the regression line of this subject lies at the border of the pressure reference area, the pressures during hoarse phonations can hardly be distinguished from the pressures during normal phonations in this subject.

The vocal efficiency in hoarse phonation is lower than in normal phonation; these efficiency values lie outside the reference area.

In summary, we may state that intentionally produced deviant phonations cannot always be distinguished in an aerodynamic inter-individual comparison (reference areas).

However, in an intra-individual comparison of phonation, with respect to the subject's regression line, the difference between hoarse and normal phonations stands out clearly. This leads to the conclusion that the initial performance of a patient or normal subject may be taken as a reference standard for evaluating changes in aerodynamic behaviour, e.g. as a result of therapeutic measures.

Chapter 5 Investigation conducted in patients

5.1 Introduction

In this Chapter that part of the research project conducted with vocal patients will be discussed.

In 5.2 a survey is given of the subject protocols of the patients, divided in three Patient Groups.

First of all, the question arises whether the aerodynamic data can be used for diagnostic purposes. To answer this question the results of the first measuring series are compared in 5.3 and the extent to which the regression lines for flow, pressure, and efficiency in the patients lie inside or outside the reference areas of the normal subjects is considered.

The results of all measuring series are given in 5.4, under the subdivisions of the three Patient Groups.

The effect of a given treatment applied to the patients was assessed by comparing the results of various measuring series in a single patient. In such cases an intra-individual comparison was made.

The discussion of the patients will remain limited to a few typical cases in each subgroup.

5.2 Survey of patients classified in Groups

The patients comprised 30 men and 37 women, selected by the random chances of clinical practice.

The majority of the patients visited the Ear, Nose and Throat Clinic of the Groningen University Hospital (Dir: Prof. Dr. P.E. Hoeksema) and the Logopedic/ Phoniatric Department because of voice or voice production complaints. All patients had in common that their voices sounded more or less abnormal.

The patients were given numbers according to the sequence of their examination.

In three Patients, Nos. 5, 17, and 22, less than 10 phonations were measured. These series were put aside. Therefore, 64 patients (29 males and 35 females) remained, see Table 5-1A and B, providing a total of 2549 phonations at various sound intensities and pitches.

In 17 patients, for various reasons, a measurement was performed only once. Three patients died, two patients underwent laryngectomy, ten patients failed to respond after repeatedly being called up, and two patients proved

Table 5-1A. Subject protocols for 29 male patients with respect to age, number of measuring series, average speaking voice pitch level (f_{mean}), and number of instances of phonation in each measuring series.

Patient No.	age years	speaking voice pitch level and number of phonations in successive measuring series							
		f_{mean}, Hz				number of phonations			
		1st	2nd	3rd	4th	1st	2nd	3rd	4th
11	47	120	125			43	33		
12	56	195	120			32	42		
13	65	125				35			
15	81	115	130			27	44		
16	42	160				27			
18	70	110	110			32	16		
21	49	110	110			53	32		
23	50	100	100			43	31		
25	70	170	165			44	24		
28	68	130	130			56			
31	37	180	145			48	52		
32	65	100	100			58	35		
33	42	120	145	135		36	22	23	
34	25	100	110	110	110	28	46	81	65
36	26	195	175			53	49		
39	73	110	110			37	27		
40	19	160	165			38	49		
41	20	140	165			26	26		
43	20	150				51			
48	19	125	110			37	47		
49	45	100	90			39	59		
50	56	120				11			
51	38	95	95			46	61		
58	20	120	130	130		76	38	53	
61	57	125	140			50	25		
64	24	125	125			46	42		
65	48	120				44			
66	72	135				16			
67	40	125				26			

Table 5-1B. Subject protocols for 35 female patients with respect to age, number of measuring series, average speaking voice pitch level (f_{mean}), and number of instances of phonation in each measuring series.

Patient No.	age years	speaking voice pitch level and number of phonations in successive measuring series							
		f_{mean}, Hz				number of phonations			
		1st	2nd	3rd	4th	1st	2nd	3rd	4th
1	49	210				24			
2	54	240	240			25	17		
3	42	200	200			31	61		
4	24	200	215	210		31	43	72	
6	63	230				17			
7	16	200				50			
8	28	210	200			35	36		
9	44	200	aphonic			24	21		
10	34	175	210	195		46	37	32	
14	48	220	235			26	72		
19	29	210	210	210		44	52	54	
20	18	200	235			45	51		
24	17	200	210			36	40		
26	31	200	195			42	39		
27	41	230	230			54	63		
29	54	190	195			35	42		
30	19	210	200			51	33		
35	22	170				26			
37	18	270				55			
38	19	220	210			41	36		
42	30	180	210			30	46		
44	20	190	190	190		42	60	68	
45	30	120	110			39	40		
46	21	200	220			42	55		
47	29	200	220			45	60		
52	16	220	230			58	30		
53	16	220				60			
54	20	210	190	200		40	59	39	
55	18	200	210			52	69		
56	46	180	230			55	22		
57	61	200				32			
59	35	220				36			101
60	23	225	210			50	43		
62	22	215				48			
63	48	165	200			24	20		

to be in too poor physical condition for further investigation.

In the remaining 47 patients (21 males and 26 females), a second measuring series was performed, totalling 1927 phonations.

For eight patients, a third measuring series appeared to be justified (422 phonations), and in Patient No. 34, we recorded four series.

The patients were divided into three Patients Groups. Many systems for the classification of vocal disturbances have been described in the past. Extensive surveys of the literature have been given by Gundermann (1970), and by Wendler, Seidner, Rose et al. (1973).

It appears that the classifications based on symptoms and signs gradually have been replaced by other classifications more closely related to aetiology and disturbed function.

Generally, vocal disturbances are divided into functional and organic disorders.

For clinical purposes, functional vocal disturbances often have been divided in a "too much effort" (hyperfunction) or a "too little effort" (hypofunction) classes. In examining the patients, an assessment is made after observation of such symptoms as the type of breathing, the use of extra-laryngeal neck muscles and the muscles of the face, and the general posture.

The vocal disturbances ascribed to organic deviations of the vocal folds have been divided in primary and secondary classes. An organic disturbance is considered to be secondary if an acute or chronic vocal misuse is supposed to be the fundamental cause of the ailment (e.g. vocal fold nodules).

For an extensive discussion of these classification, we refer to manuals on phoniatrics (Luchsinger and Arnold, 1965, 1970; Greene, 1972; Biesalski, 1973; Damstě, 1973a, b; Böhme, 1974; Boone, 1977; Wendler and Seidner, 1977; Wilson, 1979).

Our classification is primarily based on laryngoscopic findings. When a patient has such complaints as hoarseness, breathiness, huskiness, rough voice, tiredness in speaking, etc., indirect laryngoscopy is usually indicated as a first step in diagnose.

When at laryngoscopic examination an organic disturbance of the larynx was established, we have classified the patient in Group I.

Group II and Group III contain

patients with normal vocal folds.

Group II comprises the patients who were clinically characterized as having functional disturbances of the voice. The majority of these patients did not show a complete glottis closure, for unknown reasons, though the mobility of both parts of the larynx proved to be undisturbed.

In the literature, the expression "functional disturbance" is used if no organic disturbance of the larynx could be established. The organic substratum of the functional disturbances, however, as observed at indirect laryngoscopy is in most cases better designated with the diagnostic term: "slight adduction disturbance".

Group III comprises patients having normal vocal folds, but with an impaired mobility of one or both halves of the larynx due to severe disturbances of innervation.

The classification of our patients therefore is as follows:--

GROUP I. Those having organic disturbances of the vocal folds;

GROUP II. Those having normal vocal folds and, in most cases, slight adduction disturbances: "functional voice disorders";

GROUP III. Those having normal vocal folds, but suffering from severe innervation disturbances.

This classification is pragmatic useful, although, of course actually imperfect because it is based on simple laryngoscopic criteria for complex classes. Not only the nature of the vocal disturbance is quite varied, but a vocal disturbance may have various causes. In addition, a patient adapts his voice consciously or unconsciously to the residual potentialities. A vocal disturbance often shows a development depending on many factors. The appearance of symptoms or signs may therefore depend on several causes.

5.3 Results of first measuring series in all patients

The results of the first measuring series diverge considerably, because one patient is simply not comparable with another patient in reality, even if they suffer from the same affection.

Moreover, the inter-individual variations observed in the normal subjects also play a role in patients, apart from the influence of the pertinent vocal disturbance.

Figure 5-1 give all regression lines belonging to the first measuring series of 64 patients in 2549 instances of phonation.

The variations for flow as well as for pressure and efficiency are great.

5.3.1 Discussion on the aerodynamic data

Air flow rate

The regression lines for flow lie in that part of the reference area corresponding with high air flow rates, in most cases above the reference flow line. However, by far the majority lie within the contours of this area. This means that the diagnostic value of the air flow rate in phonation is small.

Data concerning the flow in vocal patients from the literature correspond with the values obtained by us (Döhne, 1944; Isshiki and von Leden, 1964; Yanagihara and von Leden, 1967; Iwata and von Leden, 1970b; Yanagihara, 1970; Iwata, von Leden, and Williams, 1972; Kelman, Gordon, Simpson et al., 1975; Gordon, Morton, and Simpson, 1978; Hippel and Mrowinski, 1978; Sawashima, Yoshioka, Honda et al., 1978).

Subglottic pressure

The regression lines for the pressure lie outside the reference area in far more patients. All regression lines in patients lie above the reference regression line.

As far as the previous literature is concerned, the subglottic pressure has been measured only in a few cases, mainly in patients with laryngeal paralysis. Comparison with our data, however, is impossible because information concerning sound intensities is lacking. These data are necessary for the interpretation of the subglottic pressure values.

Efficiency

The dispersion of the efficiency regression lines in the patients is nearly twice as large as in the normal subjects. It is obvious that the efficiency of voice production in patients is low. In Figure 5-1, it was necessary to extend the scale at the lower side by one decade for the very low regression lines.

The efficiency of an abnormal

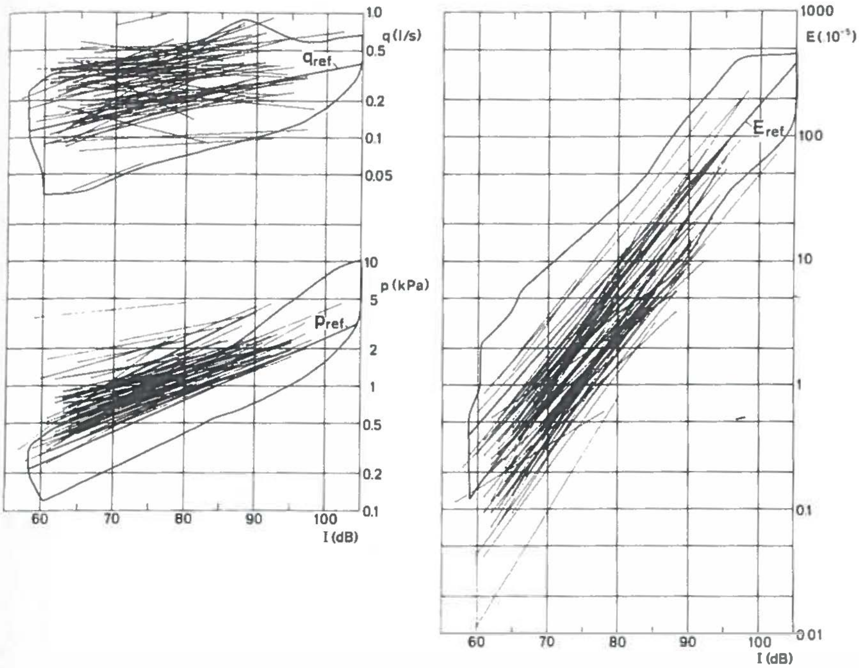


Figure 5-1. Depiction of regression lines for flow, pressure, and efficiency from the first measuring series with 64 patients, together with the corresponding reference areas. In order to represent the very low efficiency regression lines, the vertical scale was extended at the lower side by one decade.

larynx has been described in the literature for one case only, i.e. a patient suffering from an unilateral laryngeal paralysis (Isshiki and von Leden, 1964). Unfortunately, the authors mentioned neither the position of the vocal folds during phonation nor the sound intensity. Therefore comparison with our data is impossible.

Dynamic potentialities

All patients appeared to be able, though often with obviously increased effort, to reach a sound intensity of 70 dB to 75 dB, which corresponds with the sound intensity used in ordinary conversation.

The computed efficiency value is a measure for the functioning of the voice production apparatus from an energetic point of view. A low efficiency means, that in order to reach a certain sound intensity, more energy has to be supplied to the larynx. This implies that phonation will be more tiring and may cause complaints. Moreover, the larynx may then develop pathological organic disturbances, e.g. oedema of the vocal folds.

The dynamic ranges in patients are in general smaller than those in normal subjects. The patients have less potentialities of speaking loud or shouting.

Characteristic values

The characteristic values of the measuring series are recorded completely for the patients in Table 5-2 (Appendix). In the discussion of the results we shall use reduced tables, which give only the most important data.

5.3.2 Distribution of normal and deviant regression lines

A regression line has been called deviant when the midpoint of the line (i.e. I_m) lies outside the reference area.

In 20 out of 64 patients, no deviation was observed in the aerodynamic data. This means that in about 30% of the cases none of the regression lines for flow, pressure, or efficiency lies outside the reference area. For some patients this is not remarkable, e.g. Patient No. 26, suffering from a bilateral abduction paralysis, will not show deviant aerodynamic values for voice production, because nearly normal phonation is possible.

Out of the remaining 44 patients, only in 17 cases, about 40%, did the flow regression line lie outside the reference area.

The pressure regression line is deviant in 38 patients, about 85%. In 36 patients, about 80%, this is the case for the efficiency regression line.

Table 5-3 gives a classification of the regression lines for the three Groups of patients, together with the occurrence of combinations of deviant regression lines.

From Table 5-3, it is evident that the flow is never deviating alone by itself. If the flow is deviant, the efficiency, in any case, is also deviant. From this may be concluded that in the case

Table 5-3. Classification of the regression lines from 64 patients, Subdivided in the three main Patient Groups.

regression lines	number of patients	Patient Group I	II	III
deviant	44	30	9	5
flow	0	0	0	0
pressure	8	4	4	0
efficiency	2	1	0	1
flow and pressure	0	0	0	0
flow and efficiency	4	2	1	1
pressure and efficiency	17	13	3	1
flow, pressure, and efficiency	13	10	1	2
non-deviant	20	12	6	2
total	64	42	15	7

of a deviant high flow no compensation by a low subglottic pressure occurred, in which case the efficiency might fall within the reference area.

This table shows that in Group I as well as in Group II, in four patients only the pressure values are deviant. In these eight patients the high subglottic pressures are compensated by low air flow rates, which makes the efficiency values lie within the reference area.

Moreover, it appears even in Group I, that patients having organic disturbances of the vocal folds show in about 30% no deviations of aerodynamic data. To what extent this is connected with the degree of the disturbance will be discussed.

As far as Group II is concerned, most of the aerodynamic deviations were observed in pressure and efficiency values. Only in two out of nine deviant cases the flow was deviant, despite the fact that the glottis remained open in all cases.

In Group III, deviant experimental data were found in the flow as well as in the subglottic pressure data.

5.4 Results of all measuring series in all patients

5.4.1 Introduction

The aerodynamic data established in patients will be discussed in relation to clinical symptoms revealed at laryngoscopic examination. We distinguish two forms of glottis closure:--

a. The static or quasi-static glottis closure in preparation for a phonation (zero flow).

b. The dynamic glottis closure during phonation, which only can be observed at stroboscopic examination (effective non-zero flow).

The nomenclature used for the description of sound quality is restricted by us in view of the difficulty in finding terms which have the same meaning for all readers.

With the term abnormal phonatory pattern we will designate the externally visual symptoms of an incorrect type of breathing, such as upper chest or clavicular breathing, with excessive use of anterior and/or posterior strap muscles etc. during phonation.

5.4.2 GROUP I, Patients suffering from organic disturbances of the vocal folds

5.4.2.1 Introduction, division in subgroups

In 42 out of 64 patients, an organic disturbance of the larynx could be established. The character of the disturbances diverged from slight hyperaemia of both vocal folds to swollen folds with leukoplakic alteration and severely hyperplastic ventricular folds, which during phonation nearly completely cover the true vocal folds.

In Table 5-4, the 42 patients have been arranged according to the character of their clinical symptoms. In the last mentioned subgroups, the diagnosis was based mainly on data from histological examinations.

Whether or not regression lines are deviating appears to be related to the degree of disturbances of the vocal folds. In cases of hyperaemic vocal folds, all regression lines lie within the reference areas. In more severe disturbances, nearly all regression lines are deviant.

Table 5-4. Classification of the regression lines from the 42 patients with organic disturbances of Patient Group I.

organic disturbances	one or more regression lines outside reference areas		all regression lines within reference areas	
	number of pat.	Patient No.	number of pat.	Patient No.
hyperaemia	0		3	35, 48, 62
oedema	3	53, 61, 63	3	19, 29, 45
vocal fold nodules	8	7, 10, 40, 42, 44, 46, 51, 55	4	3, 49, 54, 58
polyps, cysts	6	8, 15, 21, 34, 57, 60	1	28
papillomas	2	33, 39	0	
chron. hyperplastic laryngitis, leukoplakia	5	4, 25, 65, 66 67	0	
carcinoma	6	11, 12, 13, 16, 18, 32	1	50

As far as treatment is concerned, surgical intervention, voice training, or a combination of them have to be considered.

In so-called secondary organic disturbances, e.g. hyperaemia, oedema, or nodules of the vocal folds, and sometimes also in hyperplastic laryngitis, practical experience shows that improvement may often be achieved by voice training.

In cases of organic disturbances, surgical treatment is the prevailing approach. Surgery is certainly indicated whenever the disturbance prevents or hinders a total dynamic closure of the glottis.

For a general survey of current voice therapeutic methods we refer to Damsté (1973a), Damsté and Lerman (1975), Cooper (1973), Cooper and Cooper (1977), Wendler and Seidner (1977), and for specific methods e.g. to Veldkamp (1973), Coblenzer and Muhar (1976), and to Dalhoff and Kitzing (1977a, b).

Surgical treatment nowadays generally is carried out according to the microlaryngeal method in-

Table 5-5. *Three patients, from Group I, with hyperaemic vocal folds.* Data for flow, pressure, and efficiency, derived from the regression lines at the middle of the dynamic range (I_m). The interval is the time between two successive measuring series. The value of ΔE_{rel} indicates the difference between successive E_{rel} values. For these three patients, all regression lines lie within the reference areas.

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
35		74	188	0.72	2.7	- 1.4		
48		75.5	153	1.15	2.9	- 2		voice training
	12	74	164	0.88	2.5	- 1.7	+ 0.3	
62		78	204	0.78	5.7	- 0.6		

troduced by Kleinsasser (1968).

The patients suffering from a laryngeal carcinoma received radiotherapeutic treatment. In one Patient, No. 16, suffering from a relapse of a laryngeal carcinoma, laryngectomy was necessary.

In Patient No. 65, from the subgroup chronic hyperplastic laryngitis and/or leukoplakia, a laryngeal carcinoma was established after repeated biopsies a few months after the first measuring series and a laryngectomy was performed.

5.4.2.2 Discussion on the experimental data

Hyperaemia

Three Patients, Nos. 35, 48, and 62, showed slight deviations of the vocal folds. Their regression lines all lay within the corresponding reference area, which also was the case in the second measuring series of Patient No. 48.

The values for the flow, pressure, and efficiency and the relative efficiency at I_m are shown in Table 5-5.

The values for E_{rel} demonstrate that the deviations from the reference regression line are small.

A second measuring series of Patient No. 48 resulted in values practically identical with those from the first series. This corre-

Table 5-6. *Six patients, from Group I, with oedematous vocal folds.* (For legends see Table 5-5.) The subdivision in deviant and non-deviant regression lines is made with respect to the first measuring series. A calculated value at I_m lying outside the reference areas has been marked in italics. An asterix designates a significant efficiency change (P<0.10).

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
53		79.5	175	*1.21*	6	- 1.4		advice
61		79.5	361	*1.34*	*2.7*	- 4.9		voice training
	7	84.5	235	1.33	13	- 1.2	+ 3.7*	
63		70.5	*418*	0.68	*0.6*	- 5.9		surgery +
	27	74	297	0.86	*1.4*	- 4.2	+ 1.7	voice training
non-deviant								
19		73	216	0.83	1.6	- 3		advice
	4	78	132	1.02	6.8	0.1	+ 3.1*	advice
	11	75	181	0.98	2.6	- 2.2	- 2.3*	
29		72.5	239	0.66	1.6	- 2.6		surgery
	21	77	283	0.63	4.1	- 1.5	+ 1.1	
45		81	254	0.88	8.1	- 1		advice
	11	72	244	0.59	1.6	- 2.4	- 1.4	

sponded well with the clinical findings and the symptoms of the patient. The voice training which this patient was given, but did not really wanted, yielded no improvement.

Oedema

In three of the six patients of this subgroup, see Table 5-6, one or two regression lines were deviating. The regression lines from the other three patients lay just within the reference areas.

The characteristic values for flow, pressure, and efficiency at I_m are also given in Table 5-6.

In these patients no clear relation appears between the extension of the oedema and the deviations in the aerodynamic pattern. The unilateral oedematous tissue of Patient No. 29 was much more extensive than the minimal oedema along the margins of the folds in Patients Nos. 53 and 61.

In Patient No. 29, the oedematous tissue was removed by microsurgical intervention. Patient No. 61 was given voice training. Patient No. 63, after removal of the oedematous tissue of the right vocal fold, received voice training during a short period. This patient was satisfied with the improvement to such an extent that she rejected a second intervention, intended to remove the oedematous tissue from the left vocal fold.

In three Patients (Nos. 19, 45, and 53), we could only give an advice on more effective use of their voices.

The greatest improvement was observed in Patient No. 61. In the second measuring series all regression lines fell within the reference areas.

Patient No. 19 showed remarkable changes of efficiency. In the first measuring series, the externally visual phonatory pattern was very tense. At the second series, this was not the case anymore, while an obvious improvement in the efficiency could be established. Phonation gave less trouble and the symptoms had decreased. During the third series, performed because the patient again had complaints, oedema of the vocal folds and a tense phonatory pattern could be observed once more.

In summary, it may be concluded that in patients with oedema of the vocal folds the aerodynamic data provide a varying picture without a clear relation to the degree of pathological disturbance. The presence of oedema may result in a dynamic glottis closure during phonation so that the aerodynamic data are practically normal.

Nodules

This subgroup comprises twelve patients, of which eight did show deviant regression lines and four did not, see Table 5-7.

With respect to the results of the first measuring series it can be said that the deviations, represented in E_{rel}, appear to be greater than in the cases with clinically less severe symptoms like hyperaemia and oedema.

In eight patients, the vocal fold nodules were removed by microsurgical intervention; in five of them (Nos. 7, 44, 46, 49, and 51), the clinical diagnosis of vocal fold nodules (Sängerknötchen) was histologically confirmed. In the

Table 5-7. *Twelve patients, from Group I, with vocal fold nodules.*
(For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
7		75.5	534	1.15	0.8	- 7.4		surgery
10		77.5	386	1.19	1.8	- 5.4		voice training
	4	82.5	464	1.8	3.1	- 6.2	- 0.8	voice training
	15	76	346	0.98	1.7	- 4.7	+ 1.5	
40		79	329	1.33	2.6	- 4.7		advice
	17	74.5	256	1.1	1.4	- 4.4	+ 0.3	
42		75.5	474	1.24	0.9	- 7.2		advice
	13	79	310	0.89	4.1	- 2.7	+ 4.5*	
44		78	468	1.2	1.6	- 6.1		voice training +
	2	76	459	0.97	1.3	- 5.9	+ 0.2	surgery
	9	76	295	0.89	2.2	- 3.6	+ 2.3*	
46		72	194	0.92	1.3	- 3.4		surgery
	12	78.5	142	1.21	6	- 0.8	+ 2.6*	
51		76	467	1.4	0.9	- 7.5		surgery
	10	73	329	1.02	0.9	- 5.7	+ 1.8	
55		83	512	1.62	3.5	- 6		voice training +
	11	76.5	254	1.04	2.4	- 3.4	+ 2.6*	surgery
non-deviant								
3		72.5	174	0.64	2.3	- 1.1		voice training
	6	79.5	242	0.95	5.6	- 1.7	- 0.6	
49		73	273	0.67	1.6	- 3.1		surgery
	12	76	234	0.66	3.7	- 1.3	+ 1.8	
54		78	245	0.96	3.9	- 2.3		surgery +
	9	81	299	1.59	3.8	- 4.3	- 2 *	voice training
	12	74.5	320	1.1	1.2	- 5.4	- 1.1	
58		76	325	0.65	2.7	- 2.6		voice rest +
	8	78.5	193	0.62	8.6	0.8	+ 3.4*	singing lessons
	2	81.5	256	0.83	9.6	- 0.6	- 1.4	

remaining three patients, a slight parakeratosis/acanthosis of the laryngeal mucosa (Nos. 3 and 54) was established in two cases, while a tissue sample from Patient No. 55 showed normal laryngeal mucosa.

In nearly all patients from this subgroup, the laryngoscopic examination proved remarkably that both before and after the removal (or spontaneous disappearance) of the nodules the glottis showed an incomplete closure at the dorsal part. This finding will be discussed in more detail in Section 5.4.3.

Significant improvements appeared to have occurred in Patients No. 42 (4.5 dB), No. 58 (3.4 dB), No. 55 (2.6 dB), No. 46 (2.6 dB), and No. 44 (2.3 dB).

In Patient No. 42, showing the greatest improvement with a 4.5 dB increase in efficiency, the nodules of the vocal folds were not removed; instead, she was given voice training. In this patient severe misuse of the voice (rows, shouting), in connection with domestic problems, had played an important role. At the time of the second series her problems and the misuse of her voice had decreased, which in our opinion explained the favourable result.

The improvement in Patient No. 58, a student of the Academy of Music, may be explained from the fact that in the period of the first measuring series the patient strained his voice. When his complaint started, he was conductor of a choir, gave music lessons, and was receiving singing lessons. We adviced the patient to make a less intensive use of his voice. Voice training was considered not to be necessary, because he received sufficient voice training in his singing lessons. The improvement of the efficiency in this case was mainly to be ascribed to the decrease of air consumption.

The improvement observed in Patient No. 55 cannot be attributed to recovery of the organic structure of the vocal folds. At the surgical intervention only very little tissue was removed, which appeared to be normal laryngeal tissue. The increase in the efficiency due to the decrease of the flow values has to be ascribed mainly to the effect of the voice training.

In Patient No. 46, the vocal nodules were removed by microsurgery. From the course of the disease may be deducted, that in this patient, as in Patient No. 42, an emotionally conditioned factor played a role. She changed her job, which, together with the surgical intervention, resulted in an improvement of voice production.

In Patient No. 54, a deterioration was observed, namely with respect to the pressure values.

Table 5-8. *Seven patients, from Group I, with polyps and/or cysts.*
(For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
B		75.5	341	*1.32*	*1.1*	- 6.1		surgery
	3	76	174	0.89	3.7	- 1.3	+ 4.8*	
15		81	217	*2.63*	*3.2*	- 5.1		surgery
	3	80.5	348	1.14	4.1	- 3.7	+ 1.4	
21		78.5	*420*	1.17	*2.1*	- 5.4		surgery
	4	73.5	332	*1.29*	*0.8*	- 6.6	- 1.2	
34		77.5	*541*	*1.03*	*1.5*	- 6.3		
	1	76.5	*472*	*1.08*	*1.3*	- 6.3	0	surg. + voice tr.
	2	75.5	352	0.67	2.2	- 3.3	+ 3 *	voice training
	8	77.5	377	0.92	2.3	- 4.2	- 0.9	voice training
57		72.5	125	*1.39*	*1.5*	- 3		surgery
60		73	*370*	*2.15*	*0.4*	- 9.5		surgery
	3	71.5	254	*1.35*	*0.6*	- 6.4	+ 3.1*	
non-deviant								
28		82	243	1.04	9.1	- 1.2		surgery

The tissue sample from this patient showed only few aberrations. At laryngoscopic examination it was observed that the dorsal part of the glottis, the chink, remained rather wide open. Only by great muscular effort, with high subglottic pressures, the patient was able to produce a moderately loud vocal sound. Voice training yielded no improvement of this disturbance.

Polyps and/or cysts

This subgroup comprises seven patients, the regression lines of six patients were deviant, see Table 5-8.

The clinical symptoms within this subgroup vary. Firstly, in all patients a surgical intervention with removal of the growths was performed.

In two Patients, Nos. 8 and 60, a solid tissue formation was seen on one of the vocal folds.

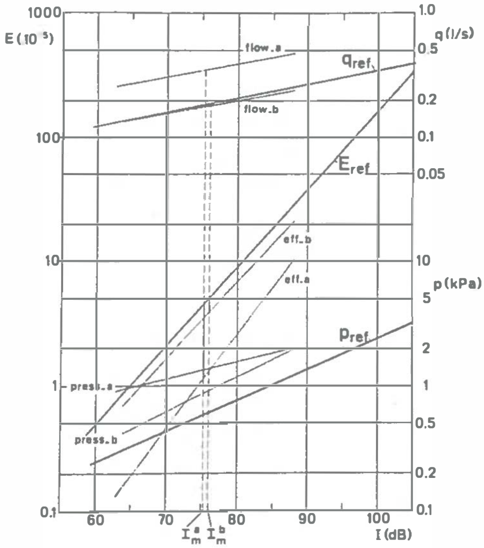


Figure 5-2.
Depiction of the regression lines for flow, pressure, and efficiency from both measuring series in Patient No. 8, represented with the corresponding reference regression lines. The data of the first measuring series have been marked with a, those of the second series with b. After the removal of the polyp, pressure values as well as flow values have decreased. The efficiency was raised and lies close to the reference regression line.

Histological examination of microsurgically removed tissue revealed sclerotic hemangioma.

Patient No. 15 had a cyst and No. 21 a polyp, the clinical diagnoses being confirmed by histological examination.

In the Patients Nos. 34 and 57, with a clinical diagnosis of polypous swollen vocal folds (polyposis laryngis), these patients proved on histological examination to be suffering from severely oedematous swollen laryngeal mucosa, with no true polyps being formed.

In Patient No. 28, the only case in this subgroup with no deviant regression lines, histological examination revealed a chronic ulcer.

The regression lines from both measuring series of Patient No. 8 are represented in Figure 5-2.

The solid growth on one of the vocal folds of this patient was localized at the free median edge. This polyp hindered of course a proper closure of the glottis during phonation. On the other hand, in Patient No. 60, the polyp was situated on the cranial side of a vocal fold. The median edges of both vocal folds showed no disturbances, and thus a good closure of the glottis could take place.

Comparing these two cases, it is clear that Patient No. 8 not only displayed a more severe dis-

Table 5-9. *Two patients, from Group I, with papillomas.*
(For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
33		79.5	234	*2.83*	*1.9*	- 6.3		surgery
	18	72	112	*1.41*	1.4	- 2.8	+ 3.4*	
	7	72.5	100	1.27	2	- 1.7	+ 1.1	
39		78.5	194	*1.5*	3.5	- 3.1		(surgery)
	17	67	266	*0.77*	*0.4*	- 5.7	- 2.6*	

turbance of the voice but also felt more uncomfortable in speaking than Patient No. 60, no doubt a simple consequence of the position of the growth. In the post-operative measuring series, Patient No. 8 was free of complaints and produced normal phonation, whereas Patient No. 60 was somewhat relieved of discomfort in phonating. Despite the significant increase in efficiency, she still showed deviant regression lines for pressure and efficiency.

In two cases a significant improvement after surgical treatment was found. Generally, as far as the results of surgical intervention are concerned, it appears that the average value of ΔE_{rel} is positive. Subjectively, most patients experienced, that phonation went more easily and was less tiring after removal of the growths.

Papillomas

In both Patients, Nos. 33 and 39, with papillomas of the adult type localized at several places in the larynx, the pressure regression lines appeared to be deviant in the first measuring series, see Table 5-9.

The data show that the subglottic pressures are high, whereas the flow values at I_m have about average levels.

In Patient No.33, a significant improvement could be established, even one and a half year after microsurgical removal of the papillomas. Multiple solitary papillomas on the true vocal fold had been removed by microsurgery. From the aerodynamic data, it

Table 5-10. *Five patients, from Group I, with chronic hyperplastic laryngitis and/or leukoplakia.*
(For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
4		71.5	196	*0.78*	1.3	- 2.8		voice training
	4	77.5	290	0.78	3.6	- 2.4	+ 0.4	voice training
	9	79	244	0.75	6.2	- 0.9	+ 1.5	
25		80.5	300	*2.1*	*2.6*	- 5.7		voice training
	13	79.5	161	*1.45*	5.5	- 1.8	+ 3.9*	
65		71	*332*	*1*	*0.5*	- 6.4		
66		69.5	*375*	*3.99*	*0.1*	-13.5		voice training
67		72.5	167	*1.41*	*1.1*	- 4.3		

appears that the flow values as well as the pressure values had decreased considerably. These data corresponded with the patient's subjective experience of lesser effort required to phonate. In a third series, seven months later, this improvement of the aerodynamic data appeared to have continued. The regression lines all lie within the reference areas.

In Patient No. 39, the first measuring series was performed after most of the papillomas on the true vocal folds had been removed for histological examination. Therefore, the result of the first measuring series of this patient is comparable with the second measuring series of Patient No. 33. The second series of Patient No. 39 showed that a deterioration had taken place, the voice having become weaker and a higher flow value and deviant pressure values at I_m having developed. At laryngoscopy, the vocal folds appeared free of papillomas, but were lesioned by the biopsies, which caused incomplete closure at phonation. In the first measuring series, reactive oedema as a result of the biopsies possibly played a role, causing a fairly proper closure of the glottis.

Chronic hyperplastic laryngitis and/or leukoplakia

This subgroup of five patients,

see Table 5-10, all of whom appeared to have one or more deviant regression lines in the first measuring series, showed a variety of clinical symptoms.

Patient No 4 had leukoplakia on the vocal folds without hyperplasia of the ventricular folds, whereas in Patient No. 66 the vocal folds had since years been severely swollen, with very hyperplastic ventricular folds. Extensive leukoplakic areas were present on the true vocal folds as well as on the ventricular folds. In both patients, a very tense phonatory pattern could be observed.

In Patient No. 66, the organic condition of the larynx had been changed so much that the vocal folds could scarcely be brought to vibration. The ventricular folds hindered the true vocal folds in their action. The relative efficiency value was very low, -13.5 dB.

Patient No. 4 was given voice training, and the phonatory pattern improved but a significant increase in the efficiency could not be established.

Both measuring series from Patient No. 25 represent intermediate stages in an improving phonatory pattern with simultaneous improve-

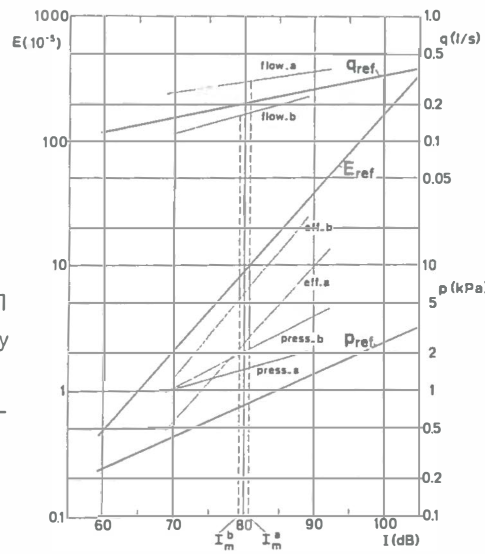


Figure 5-3.
Depiction of the regression lines for flow, pressure, and efficiency from both measuring series in Patient No. 25, represented with the corresponding reference regression lines. The data of the first measuring series have been marked with a, those of the second series with b. In this patient with chronic hyperplastic laryngitis, the phonatory pattern improved in the course of about one year, partly as the result of voice training. The improvement in aerodynamic data can be observed from the decrease of the flow values and, to a lesser degree, of the pressure values. The relative efficiency had increased by 3.9 dB.

ment of the laryngeal organic condition, see Figure 5-3.

This patient had been classified in this subgroup because nine months prior to the first measuring series a laryngitis with leukoplakia had been established. Microscopic examination of the tissue removed at direct laryngoscopy yielded a diagnosis of severe dysplasia, with the comment added, "It is a matter of opinion whether it is severe dysplasia or carcinoma in situ." Radiotherapy was considered, but finally not applied. The patient was asked to come in for regular follow-up examinations. He was very pleased to make these visits, feeling reassured when everything still appeared to be all right. Gradually, the voice improved and the laryngitis symptoms disappeared. The very tense phonatory pattern, which was apparent from the beginning, still remained and the average speaking voice pitch level was remarkably high. This can be seen as a sign of his emotionality. The dynamic potentialities of the voice (phonetogram), however, were good. Voice training was started, but, due to an intercurrent disease, soon stopped. At the second series, the phonatory pattern was much less tense. From the aerodynamic data, it appeared that the pressure values were lower, This yielded an ultimate improvement in relative efficiency of 3.9 dB.

Squamous carcinoma

This subgroup comprises seven patients with a squamous carcinoma of the laryngeal mucosa, see table 5-11. Six of these seven patients had a squamous carcinoma of the vocal folds. There were differences in the site and extension of the carcinoma. In Patient No. 50, the true vocal folds were not affected, the tumour was situated on the inner side of the epiglottis and left the vocal folds free. In this patient the regression lines were not deviant.

In all patients of the deviant group, we found a very tense phonatory pattern. At laryngoscopic examination hypertrophic ventricular folds were found. Moreover, during phonation these ventricular folds were more or less brought to adduction and, therefore, interfered with the correct vibration pattern of the true vocal folds.

In Patient No. 11, the pathologist initially diagnosed the biopsy as severe dysplasia. After a second opinion, the pathologist's

Table 5-11. *Seven patients, from Group I, with squamous carcinoma.* (For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
11		73	354	0.97	0.8	- 5.8		biopsy
	24	77.5	314	1.1	2.3	- 4.2	+ 1.6	
12		72.5	171	1.88	0.8	- 5.7		radiotherapy
	19	80	98	1.58	9.3	0.2	+ 5.9*	
13		71	307	0.7	0.8	- 4.5		radiotherapy
16		75	489	1.28	0.7	- 7.7		
18		80.5	364	1.45	3.1	- 5		radiotherapy
	21	75	232	0.95	2.1	- 3.2	+ 1.8	
32		76.5	249	1.58	1.6	- 5.1		radiotherapy
	13	79.5	145	1.01	8.8	0.2	+ 5.3*	
non-deviant								
50		75	205	0.78	2.9	- 1.8		

advice was to consider the disturbance as an early invasive squamous carcinoma. Shortly thereafter, new biopsies lead to the diagnosis of carcinoma in situ. Radiotherapy was considered but finally not applied. Based on the undisturbed clinical appearance of the vocal folds, it was decided not to operate, but frequently to follow up the patient. In retrospect, we may assume that the extension of the carcinoma had been so little that in taking the biopsies, all pathological tissue had been removed. The aerodynamic pattern was deviant, although the vocal folds at the moment of the measuring series were hardly affected. At stroboscopic examination the vibration pattern of the right vocal fold seemed to be influenced by rigid scar tissue. The phonatory pattern was very tense and remarkably hyperkinetic.

The patient frequently visited our out-patient department for follow-up examinations. The appearance of the vocal folds and the findings at stroboscopy in later years gave no reason for further investigations. In the two years between the first and second measuring series, the voice gradually became less hoarse. In emotionally stressed situations though, the patient still had periods in which his voice sounded hoarse. During the second measuring series, the voice sounded practically normal. The vocal folds had a normal appearance and the hypertrophia of the ventricular folds had decreased considerably. The efficiency of the larynx improved, but the subglottic pressures remained rather high.

For the interpretation of the aerodynamic data it is of importance to note that the values for pressure and efficiency were deviant, whereas the vocal folds showed only few aberrations. We may conclude from these observations that sometimes there is no obvious relation between the aerodynamic data and the laryngoscopically visible condition of the vocal folds. Sometimes the appearance of the vocal folds is much better than the aerodynamic data would suggest.

Despite the small deviations of the vocal folds, the relative efficiency in Patient No. 11 is -5.8 dB. The hypertrophia of the ventricular folds and the fact that these folds nearly completely cover the true vocal folds during phonation, has a great influence on the efficiency of voice production. The appearance of hypertrophia of the ventricular folds at laryngoscopy ought also to be judged as a sign of hyperfunction. This hyperfunction will also be found in the externally visible phonatory pattern.

In Patient No. 18, we observed a very limited lesion on one of the vocal folds. The histological examination lead to the diagnosis of well differentiated squamous carcinoma. The patient was given radiotherapy, and the voice gradually improved. At the second measuring series, the vocal folds were normal, moreover, the hypertrophia of the ventricular folds had decreased.

Both Patients (Nos. 11 and 18) showed a very tense and hyperkinetic phonatory pattern, with costal and sometimes paradoxical respiration. Initially the voices were very dull, with much wild air. After X-ray treatment, the flow values were not deviant, both voices sounded clear and the phonatory pattern was less tense.

The great improvement in the aerodynamic data of the Patients

Nos. 12 and 32 is remarkable.

In Patient No. 12, the sudden improvement of the vocal symptoms was conspicuous. The voice problems of this patient arose after an automobile accident. Initially, the patient was aphonic for some days, then the voice returned. Laryngeal injury was out of the question. The voice remained hoarse and the average speaking voice pitch level was remarkably high (G3, 195 Hz). Very severe hypertrophic ventricular folds were observed at laryngoscopic examination. On one of the vocal folds appeared to be a tumour, suspected of being malignant. A biopsy revealed the diagnosis of squamous carcinoma. The patient was given radiotherapy.

Initially the phonatory pattern was very tense, with high and paradoxical respiration and much wild air. Until shortly before the end of the X-ray treatment the voice remained high-pitched and very hoarse. Even more remarkable was the fact that the voice improved from one day to the next, the average speaking voice pitch level sinking to the usual level for men. In the second measuring series, the voice was clear, the vocal folds were normal, and hypertrophia of the ventricular folds could not be observed anymore. The dynamic potentialities also increased, as is apparent from the increase in I_m. Despite this improvement, the subglottic pressure remained relatively high and deviant. The efficiency, however, increased due to the decrease of the flow values.

Patient No. 32 had a long history of vocal complaints with a pronounced fear "that something was wrong with his throat". A local thickening on one of the vocal folds was found at laryngoscopic examination. From the biopsy material, the pathologist reported "well differentiated squamous carcinoma with infiltrative growth". The phonatory pattern was very tense and hyperkinetic and voice production demanded much effort. Radiotherapy was given. At the second measuring series, the phonatory pattern was still very tense. However, sometimes a more relaxed phonatory pattern could be observed. After treatment, the regression lines for subglottic pressure and efficiency were not deviant anymore.

5.4.2.3 Conclusions

We may summarize our conclusions about the patients in Group I as follows:--

a. Generally speaking, a relation exists between the degree of clinically observed disturbances and the deviations of the aerodynamic pattern of voice production.

b. The deviations of the aerodynamic data are often larger than the organic appearance of the vocal folds might suggest. This seems to be strongly correlated with a tense and hyperkinetic phonatory pattern. Though in some cases removal of the organic aberration was sufficient to enable the patient to realize a complete dynamic closure, voice training was often necessary to teach the patient how to get rid of this established habits of hyperkinetic and tense phonatory pattern.

c. Surgical therapy as well as voice training, in general, may yield improvement of laryngeal efficiency.

d. Improvement of laryngeal efficiency depends on the possibility of dynamic glottis closure during phonation. The result of removing a polyp from the free margin of a vocal fold is therefore more effective than the removal of a nodule on a vocal fold, because in the latter case the dynamic closure of the glottis hardly shows any improvement.

e. The majority of the patients with vocal nodules showed an incomplete closure of the glottis. This fact seems to be more important than the presence of the nodules itself.

f. If an organic disturbance hinders a complete dynamic closure of the glottis and the flow is about normal, the subglottic pressures commonly are found to be high. The increased subglottic pressure seems to be the consequence of the increased muscular effort necessary to effectuate a proper closure of the glottis. After removal of the organic disturbance a complete dynamic closure is possible with lower subglottic pressure and flow values.

5.4.3 GROUP II, Patients having normal vocal folds and, in most cases, slight adduction disturbances: "functional voice disorders"

5.4.3.1 Introduction, speech therapist's diagnosis

In 15 out of 64 patients no organic disturbances of the vocal folds or severe innervation disturbances could be detected.

We were struck, however, by the fact that in the majority of the patients of Group II the glottis at the dorsal side, as visible in the mirror, was not completely closed during phonation. Complete closure could not be observed in stroboscopic examination either.

Koike and Hirano (1973) drew attention to the occurrence of this incomplete closure of the cartilagenous part of the glottis (the chink), writing, "A physiological fact that has often been overlooked or ignored ... This fact has not drawn much attention so far, perhaps because of the difficulty in its observation."

Farnsworth (1940) as well as Schönhärl (1960) observed this phenomenon in normal subjects with normal sounding voices.

With this incomplete closure of the glottis, the vocal intensity decreases and hoarseness occurs. This decrease has also been proved by experiments with the prepared human larynx (van den Berg and Tan, 1959; Tan, 1960).

It is difficult to trace the cause of an incomplete closure of the glottis. A slightly imperfect formation of the laryngeal skeleton (cartilages, cricothyroid joint), or of the vocal folds (e.g. hypoplasia or a sulcus glottidis) as well as slight innervation disturbances of the internal laryngeal muscles all are possible.

A dyssynergia may express itself in an improper mutual adjustment of the interarytenoid, lateral cricoarytenoid, vocalic, and cricothyroid muscles. These muscles effectuate a proper adjustment of the vocal folds as a counterbalance of the expiratory subglottic pressure. Moreover, a faulty use of the larynx, intentional or not, may also lead to the habit of improper muscular adjustment and a persistent hoarse voice. This characteristically occurs, when the speaker wishes to achieve a certain vocal effect, as a realization of the personal role he tries to play ("voice image", Cooper, 1973).

Sedláčková (1960) pointed out the possibility that straining of the voice during childhood may lead to permanent changes of the microstructure of the vocal folds. In later years, this is supposed to lead to an atrophic aspect of the vocal folds and incomplete closure of the glottis.

In clinical practice when patients do not show any organic disturbances usually consultation by a speech therapist will take

Table 5-12. A classification of the regression lines from the 15 patients of Patient Group II, i.e. those having normal vocal folds and, in most cases, slight adduction disturbances, the so-called functional voice disorders. In the first part of this Table, a classification on the basis of laryngoscopic findings is followed and in the second part a classification on the basis of the diagnosis of the speech therapist.

	one or more regression lines outside reference areas		all regression lines within reference areas	
A. indirect laryngoscopy	number of pat.	Patient No.	number of pat.	Patient No.
no disturbances	2	14, 31	1	27
hyperfunction on ventricular fold level	0		2	38, 64
incomplete glottis closure	7	20, 24, 30, 36, 41, 47, 52	3	37, 43, 59
B. speech therapist's diagnosis				
hypokinetic	0		1	37
hyperkinetic	0		2	38, 59
dyskinetic (mixed hypo- and hyperkinetic)	5	20, 24, 30, 47 52	0	
mutational disturbance	1	41	2	43, 64
psychogenic dysphonia	1	14	1	27
spastic dysphonia	1	31	0	
dysphonic falsetto	1	36	0	

place, e.g. for establishing the phonatory pattern, and also for planning a proper vocal rehabilitation programme.

The therapeutic possibilities in these patients with functional disturbances are limited to treatment by voice training. A complete recovery from the disturbances is in most cases not possible. The voice lessons will be mainly aimed at an optimal use of the larynx, which means training to acquire a more relaxed phonatory pattern.

This can only result in improvement within the limits of the possibility of functional adaptation of the laryngeal structures of the patient. After voice training it was often found that the patient had fewer complaints of fatigue after speaking for a long time and less discomfort of the neck muscles etc. Laryngoscopy, however, often shows that the slight adduction disturbances are still present to an undiminished degree. The result of voice training, therefore, cannot be established by laryngoscopy alone.

A better voice will be related to a decreased open quotient, therefore the mean flow value at phonation may be expected to become smaller.

Table 5-12 gives a survey of the regression lines of the patients in this group. In nine out of fifteen patients we found one or more deviant regression lines. The remaining six cases had no deviant regression lines.

5.4.3.2 Discussion on the experimental data

In Table 5-13 the values for flow, pressure, and efficiency at I_m have been recorded. From an aerodynamic point of view the patients show a fairly uniform pattern, despite differences in the speech therapist's diagnosis. Moreover, it is notable that in the ten patients with incomplete glottis closure a deviant high flow was observed in only two cases whereas six showed a subglottic pressure which was too high.

A significant improvement in E_{rel} could be ascertained in four Patients, Nos. 20, 30, 36, and 47.

Patient No. 20 had a rough and hoarse voice, which was not uncommon in her relatives. The patient had been hoarse "from birth on".

Even after treatment the quality of the voice scarcely changed. There can be no doubt, however, that there was a significant improvement in the patient, not only in vocal efficiency, but subjectively also. She felt she was able to speak with lesser effort. This must be explained in terms of an adaptation by the patient of her own phonatory pattern to the functional limitations of her laryngeal structures in order to achieve an optimal result with minimal effort.

The improvement of the efficiency in Patient No. 30 was also remarkable. This improvement can only be ascribed to a change in the phonatory pattern probably caused by psychological factors. The improvement began after the patient left her nurses' training school. She had found this training too demanding and it had affected her emotionally. In the first, as well as in the second measuring series, her glottis appeared not to close at the dorsal side. Nevertheless, at the second measurement, the efficiency of the voice production had increased and phonation demanded much less effort.

In the same way, in the other cases in which an improvement was found, it could also be established that the glottis closure had hardly improved. The closure at the dorsal side was still incomplete at the second measuring series in most cases.

Sulcus glottidis

In Patient No. 36, with apparently normal vocal folds, but also with an incomplete glottis closure, the laryngoscopic findings were interpreted finally as due to a congenital hypoplasia of the larynx. Both vocal folds showed longitudinal grooves and underdevelopment. A good chest voice quality could not be produced. The speech therapist therefore rightly described the voice of this patient as "dysphonic falsetto voice".

After voice training, this patient had clearly learned to phonate at lower subglottic pressures, which was the cause of a considerable part of the improvement achieved in the efficiency. The speaking voice pitch level remained high for a male voice, at about F3, (175 Hz). The sound quality became somewhat less shrill possibly because he had learned to bring the epiglottis in the direction of the arytenoids at phonation.

Psychogenic dysphonia

Two Patients from Group II (Nos. 14 and 27) deserve special attention. They are striking by their decrease of efficiency as established in the second measurement. Patient No. 14 who could only phonate in a squeaky voice in the first measuring series seems to have been able to do this with more efficiency than was possible for her in the second measuring series where she was able to phonate normally. In both patients there was question of psychogenic dysphonia with, especially in

Table 5-13. Fifteen patients of Patient Group II, i.e. those having normal vocal folds and, in most cases, slight adduction disturbances. (For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
14		68.5	46	*0.78*	2.8	2.3		
	6	79	244	0.75	6.2	- 0.9	- 3.2*	
20		78	289	*1.11*	2.8	- 3.7		voice training
	14	84.5	176	1.5	15.4	- 0.5	+ 3.2*	
24		78.5	333	*1.12*	*2.7*	- 4.2		voice training
	13	73	197	*0.81*	1.8	- 2.5	+ 1.7	
30		77	*399*	0.88	*2.1*	- 4.5		voice training
	14	79	286	0.81	4.9	- 1.9	+ 2.6*	
31		75.5	140	*1.02*	3.6	- 1.1		psychiatry
	14	78	191	1	4.8	- 1.4	- 0.3	
36		76.5	281	*1.6*	*1.4*	- 5.7		voice training
	13	75	239	*0.94*	2	- 3.2	+ 2.5*	
41		77	*444*	*1.02*	*1.6*	- 5.5		voice training
	14	73.5	324	0.68	*1.5*	- 3.7	+ 1.8	
47		75.5	179	*1.08*	2.7	- 2.4		voice training
	7	74	172	0.63	3.4	- 0.4	+ 2 *	
52		75	299	*0.88*	*1.7*	- 3.9		voice training
	11	75.5	302	0.7	2.4	- 2.8	+ 1.1	
non-deviant								
27		78.5	86	0.83	14.3	3		
	13	76.5	155	*1.05*	4	- 1.3	- 4.3*	
37		77.5	161	0.69	7.3	0.7		
38		77	158	0.79	5.8	0.1		voice training
	17	73	147	0.71	2.6	- 0.9	- 1	
43		81.5	206	0.97	10.3	- 0.3		
59		79	102	0.86	13	2.3		
64		80	289	1.05	4.8	- 2.7		voice training
	3	76.5	265	0.9	2.7	- 3	- 0.3	

No. 14, a very peculiar aerodynamic pattern, see Figure 5-4.

The psychogenic dysphonia in Patient No. 14 appeared to be connected with severe domestic problems. When these problems were solved, her voice recovered gradually. At the first measuring series, the patient produced a squeaky voice, at the second measuring series her voice did not sound deviant anymore.

In the first measuring series of Patient No. 27, she complained that phonation was very tiring. The voice often sank away and the patient became aphonic. In the past she suffered repeatedly from a psychogenic aphonia. In these cases the voice returned spontaneously after some time. At the second measuring series, the patient had no complaints about her voice and her phonation was quite normal again.

In both patients, the aerodynamic pattern became normal, which is also reflected in the experimental data e.g. by the better dynamic range in Patient No. 14.

Spastic dysphonia

In Patient No. 31, we diagnosed spastic dysphonia.

This seems to be a disorder of the vocal attack rather than of phonation as such. It seems to be characterized "by a strained, creaking, and choked vocal attack, a tense and squeezed voice sound that is accompanied by extreme tension of the entire phonatory system" (Berendes, 1938; Brodnitz, 1976), or of the continuity of phonation, in which "the breath stream is at times being locked by a stiffly closed glottis" (Damsté, 1973, 1978; Damsté and Lerman, 1975).

This is born out by the experimental data that show that after the onset of phonation the efficiency of the larynx differs only little from the reference value.

General discussion

Roughly speaking, there is a certain similarity between the patients of Group II (Table 5-13) and the patients with vocal nodules from Group I (Table 5-7). In the latter subgroup we often observed that during phonation the glottis remained open at the dorsal part, even after surgical removal of the nodules.

In both groups the values of the subglottic pressures at corresponding values of I_m are high. The high subglottic pressures of the patients in both groups, which they obviously require for phonation, indicate that these patients effectuate the closure of the glottis with a special effort. Therefore, a greater subglottic energy is necessary to keep the vocal folds vibrating, and the greater muscular effort of the respiratory system and the larynx will lead to tiredness and complaints.

The fact that at an incomplete dynamic closure of the glottis and a normal flow value a raised subglottic pressure may be found, seems at first sight paradoxical. A low value for the subglottic pressure might have been expected.

It is likely that a patient will try to overcome his soft voice (in consequence of the incomplete closure of the glottis) by additional contraction of the adducting muscles. Sometimes this may be observed as a synergetic adduction of the ventricular folds. This can be explained as a consequence of the greater muscular effort of the patient trying to close the glottis. The striated muscles perform extra work and thus get sooner tired. This leads ultimately to a hyperfunctional use, because

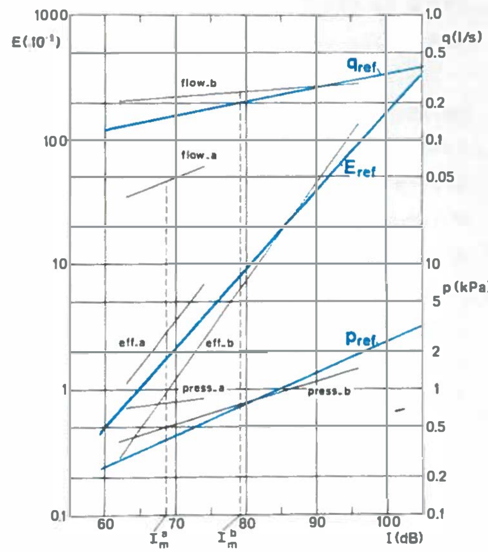


Figure 5-4.
Depiction of the regression lines for flow, pressure, and efficiency from both measuring series in Patient No. 14, represented with the corresponding reference regression lines. The data of the first measuring series have been marked with a, those of the second series with b. This patient had a psychogenic voice disorder with a high-pitched squeaky voice. At the first measuring series, the voice was soft, although with a high efficiency, which appeared mainly to be the result of the low flow values. At the second series, the voice did not sound deviant anymore, and the potentialities of the voice appeared also to be normal, resulting in practically normal aerodynamic data.

there is relatively excessive tension.

The raised subglottic pressure reflects this extra effort of the respiratory muscles as well as of the intrinsic laryngeal muscles, which must have a higher tension at a raised subglottic pressure. In this way more internal tension in the laryngeal muscles themselves is produced by an increase in the longitudinal tension (cricothyroid muscle), an increase in the medial compression (lateral cricoarytenoid muscles), and an increase in the internal tension in the vocal fold (internal thyroarytenoid muscles).

A generally raised tonicity of the striated musculature, e.g. in emotionally tense persons, also leads to a tense phonatory pattern, usually as well observable in their outward appearance.

The excess tension in the vocal folds influences the flexibility of their movements, both in the muscular part as well as in the superficial layer of epithelial tissue; because of this the displacement amplitude of the vocal folds will be less during a vibration circle. One should expect accordingly a lower air flow rate to be measured. However, the quasi-static incomplete closure of the glottis prevents a decrease of the flow due to reduced displacement amplitudes. Because of the lesser displacement amplitudes of the vocal folds the air stream is, at the same time, less fully modulated, producing a softer basic sound.

The augmented subglottic pressure, conditioned by the subject's effort to speak louder, contributes further to elevate the flow rates, spilling subglottic power to the detriment of the efficiency of the voice production. This vicious circle has as result that the exerted effort and the subject's fatigue increase out of proportion to the achieved sound intensity.

It should also be taken into account that at increasing sound intensity the adductory effect of the laryngeal muscles has to be greater in order to achieve an adequate closure of the glottis. In patients with slight adduction disturbances the phenomena observable during soft phonation resemble those occurring in normal subjects in loud phonation.

The clinical importance of helping the patient escape from the vicious circle in which additional phonatory effort yields diminishing returns, cannot be stressed too strongly.

As a result of voice training

patients may achieve the ability of phonating at lower subglottic pressures and a less tense adjustment of the vocal folds, permitting a more flexible vocal fold mobility. Accordingly, too, the full advantage of the Bernoulli effect can be realized and the vocal folds will close the glottis earlier during a vibration cycle, causing the open quotient to be smaller.

Consequently, then, the average air flow rate will decrease and the sharper wave shape of the glottis pulses will enrich the harmonic structure of the basic sound. In patients who phonate without a complete glottis closure in the vibration cycle, a more relaxed style of phonation may clearly yield a better modulated air stream. Whether this will also decrease the air flow rate significantly or not will depend on the size of the resulting effective quasi-static opening of the glottis and the ultimate height of the subglottic pressure.

The lower subglottic pressure will diminish the amount of wild air and the stream velocity, thus reducing the factors giving raise to turbulence. Breathiness will be less conspicious or even become inaudible.

The amount of wild air in certain cases, however, may be such that even after treatment the voice remains breathy. Nevertheless, by reduction of the effort needed for a certain sound intensity, voice production even in these cases will be less tiring, and the patient will experience this subjectively as an improvement. Objectively the improvement may be ascertained in a decrease of the subglottic pressure values.

5.4.3.3 Conclusions

Summarizing, we can make the following statements with respect to the patients from Group II:--

a. Even with an incompletely closed glottis phonations at normal intensity levels can be produced without high air flow rates.

b. Psychogenic influences on the voice production may sometimes be revealed in the aerodynamic pattern.

c. Voice training generally leads to improvement of the efficiency. In these cases, both the functional possibilities and limitations of the physiological structures available for phonation and the aerodynamic factors in phonation should be taken into account in planning treatment and evaluating as well as predicting its result.

5.4.4 GROUP III, Patients having normal vocal folds, but suffering from severe innervation disturbances

5.4.4.1 Introduction

Laryngoscopy of a normal larynx shows that each vocal fold may assume any of a continuum of quasi-static positions, depending on laryngeal function: breathing, phonation, whispering, swallowing, coughing, etc. This is realized as a result of the mobility of the arytenoids and the contraction under neuromotor control of the muscles inserted into the muscular processes. For a discussion of these positions we adopt the rough classification of Jeschek (1953, 1958) and Luchsinger and Arnold (1965), see Figure 5-5.

During normal respiration, both vocal folds are abducted and they occupy a prelateral position. In forced respiration they move into the lateral position. These two positions will only seldom be found as permanent positions in cases of disturbed innervation.

The effect of paralysis of one or both laryngeal halves on voice and respiration depends on the position in which one or both vocal folds remain fixed.

The clinical symptoms and signs resulting from laryngeal paralysis are related to two factors:--

a. Whether the paralysis is unilateral or bilateral. (For bilateral paralysis the well-known thumb role is applicable: the wider the glottis opening at respiration, the worse will be the voice and vice versa.)

b. The position of the vocal folds during respiration and during phonation.

When in unilateral paralysis the affected vocal fold stands still in median position, the voice will be about normal and respiratory difficulties will not occur in ordinary circumstances. While there will be no respiratory problems in case of unilateral paralysis with fixation of the affected fold in paramedian or intermedian position, in the latter case voice production results in a very breathy quality.

The vocal fold at the non-paralysed side can be normally adducted and sometimes appears to surpass the median line. Compensation is usually possible for a fixed position of one vocal fold up to the paramedian position. Such a compensation is usually effectuated as a gradually developing adaptive process, in which the voice is initially hoarse, but gradually becomes normal.

Compensation may occur as well by adductory movements in the region of the ventricular folds, inter alia by contraction of the extrinsic laryngeal muscles.

Several authors, Stern (1929), Döhne (1944), and Arnold (1948, 1955a, b, 1958, 1959), have presented tables summarizing their observations of the typical course of changes of the voice in acute as well as gradually developed laryngeal paralysis. However, it seems to be very difficult to describe general and characteristic changes of vocal qualities in connection with various stadia of paralysis.

Of practical importance is the fact that laryngeal paralysis is a process in which a stationary condition developes only after a certain course of time. There is no common consensus as to the desirability of voice training in these cases.

During rest, a unilateral paralysis causes no respiratory difficulties; in case of great effort though some dyspnoea may occur (Berendes, 1956).

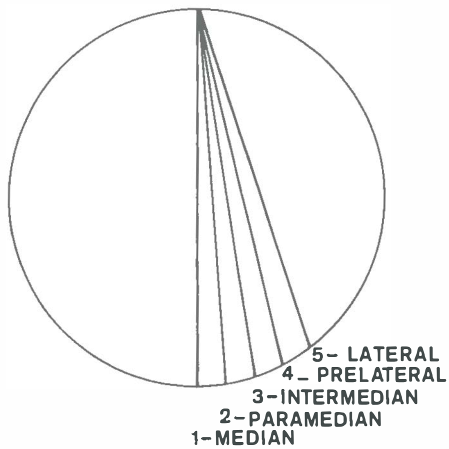


Figure 5-5.
Classification of the positions in which the vocal folds can be seen at laryngoscopic examinations.

In case of bilateral laryngeal paralysis with both vocal folds fixed in median position severe respiratory difficulties will occur, appearing as inspiratory stridor and dyspnoea, even at rest. In such cases, there will of course be no problem in common phonating.

In bilateral laryngeal paralysis with both vocal folds in a fixed intermedian position the glottis is rather wide. However, there may here be other respiratory problems of quite a different nature and the patient will speak with a whispering voice, using much air. The inspiration of air is not hindered, but the rhythm of the respiration may be severely disturbed and the patient often complaints of dyspnoea. Moreover, symptoms of hyperventilation may appear.

These respiratory problems need not be the result of local difficulties in pulmonary ventilation, but can be related to changes in the kinaesthetic system, influencing the proprioceptive reflexes which regulate the respiratory rhythm (Gould, 1971). The lungs are deflated too quickly as a result of the high flow during phonation, which is accompanied with fairly high alveolar pressures.

During phonation the vocal folds can move to the midline position as a result of the Bernoulli effect and the elastic recoil from a previously sidewards displacement produced by aerodynamic factors. The interacting effects of subglottic pressure, elasticity, and the Bernoulli effect is maximal in vocal folds which are not tensely stretched. The degree of internal tension of the vocal folds, therefore, is also of importance. This depends mainly on the activity of the cricothyroid muscle.

In Group III, comprising seven patients a cross section of the typical clinical aspects of laryngeal paralysis is present, see Table 5-14. The subgroup unilateral paralysis consists of three, the one with bilateral paralysis, of four patients. In both subgroups, there is one single patient whose regression lines all lie within the reference areas. Figure 5-6 gives a survey of the findings at laryngoscopy.

5.4.4.2 Discussion on the experimental data

Unilateral laryngeal paralysis

The results of the measuring series from the three patients are summarized in Table 5-15.

Patient No. 2, a woman of 55 years, having a paralysis of the left side of the larynx, of unknown cause. At the time of the first measuring series the paralysis had lasted 1B years.

Although the right vocal fold at phonation surpassed the median

Table 5-14. A classification of the regression lines from the seven patients of Patient Group III, in whom a disturbance of the mobility of one or both laryngeal halves could be established.

innervation disturbance	one or more regression lines outside reference areas		all regression lines within reference areas	
	number of pat.	Patient No.	number of pat.	Patient No.
unilateral	2	2, 6	1	26
bilateral	3	1, 9, 56	1	23

line, the compensation was not adequate. The voice was soft and speaking was tiring. About two years later, at the second measuring series, a slight deterioration appeared to have developed. This corresponded with the subjective experience of the patient. She complained more than before about difficulty in breathing and dyspnoea, which corresponded well with the higher air flow rate at I_m. The relative efficiency was very low (-9.4 dB).

Patient No. 6 was a woman of 64 years with a paralysis of the left side of the larynx caused by metastases of breast cancer.

There were few signs of compensation by the right side, possibly because the paralysis had only lasted a fortnight at the time of measuring. The voice was soft and phonation demanded much effort. The efficiency line was deviant, because flow and pressure ran just at the border of the relevant reference areas. Because of the death of the patient, a second measuring series did not take place.

Patient No. 26 was a woman of 32 years with a paralysis of the left side of the larynx, which at the time of the first measuring series had lasted 5 years.

The affection started during a viral infection as a bilateral paralysis with both vocal folds in median to paramedian position. Later, the mobility of the right side of the larynx returned, leading to the disappearance of the respiratory difficulties. At the time of the first measuring series a good compensation by the

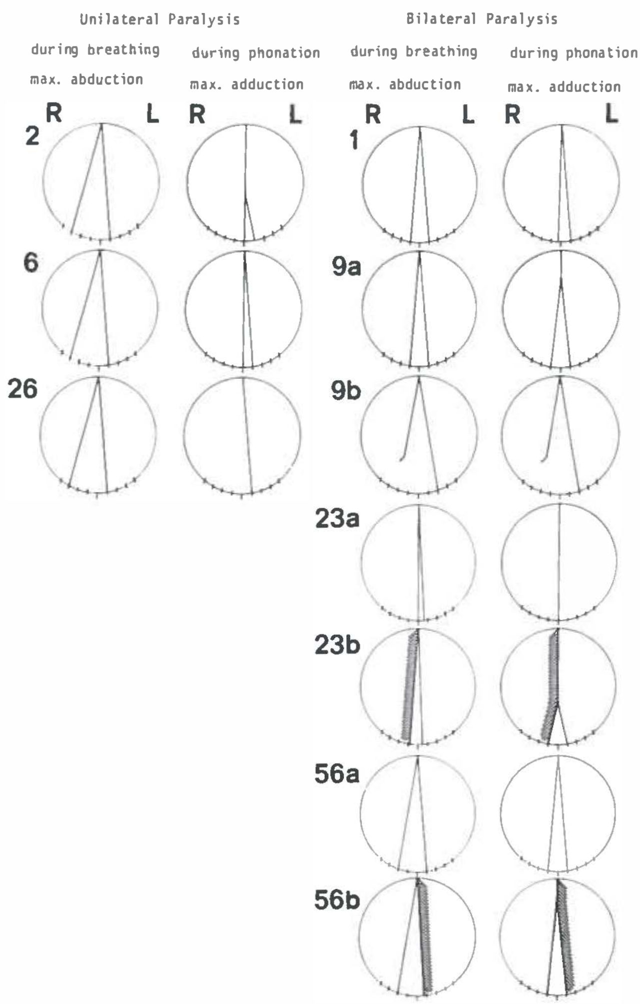


Figure 5-6. A survey of the laryngoscopic findings during respiration and phonation in seven patients with severe innervation disturbances of the larynx. (Shading: ventricular folds)

Table 5-15. *Three patients, from Group III, with an unilateral innervation disturbance.*
(For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB
deviant							
2		69.5	*432*	*0.98*	*0.3*	- 8	
	27	71	*681*	*0.97*	*0.3*	- 9.4	- 1.4
6		70	293	0.67	*0.7*	- 4.5	
non-deviant							
26		80	212	1.01	6.7	- 1.2	
	14	79	172	*1.22*	5.4	- 1.5	- 0.3

right side existed, since the right vocal fold surpassed the median line at phonation. The voice was practically normal, this patient partook of amateur acting in a club without having any problems with her voice. In aerodynamic respects, the values for pressure were on the high side, however still within the limits of the reference area. The regression lines for flow and efficiency differed only very little from the reference regression lines.

At the second measuring series, about one year later, the efficiency at the middle of the dynamic range had remained nearly at the same value as in the first measuring. The patient told us, though, that phonation caused her more discomfort. This corresponded well with the fact that a deviating regression line for subglottic pressure was measured. For the usual sound intensities of ordinary conversation, the larynx was well compensated, but at louder speech a deviant aerodynamic pattern appeared rather soon, because the air flow rate and the subglottic pressure increased too quickly (large values of the regression coefficient b).

Bilateral laryngeal paralysis

The results concerning all four patients from this subgroup, have been represented in Table 5-16.

Three patients showed deviant regression lines in the first measuring series. In connection with the existing difficulty in breathing, in three patients it was necessary to widen the glottis by surgical intervention.

Patient No. 1 was a woman of 49 years old, suffering from a bilateral paralysis after thyroidectomy, which at the time of the first measuring series had lasted for two years.

The patient had a rough and hoarse voice, and, at respiration, the glottis was not wide enough.

She complained about dyspnoea, which she experienced at the least effort. Her left vocal fold stood still in a paramedian position with little possibility of movement towards the median line. At phonation the left vocal fold touched the right vocal fold which stood still in paramedian position. At stroboscopic examination an irregular vibration pattern was observed, with a short closed phase.

The efficiency, at -9.1 dB, was very low. Though the glottis was practically continually open, the air flow rate was not deviant. The subglottic pressure was much higher than normal.

In this patient the respiratory problems made a surgical widening of the glottis necessary. However, the patient died soon after the first measuring series because of developing metastases of the malignant thyroid neoplasm.

Patient No. 9 was a woman of 44 years with a bilateral laryngeal paralysis which had developed after a thyroidectomy one year previous to the first measuring series. At first both vocal folds stood in practically median position (posticus paralysis) with severe respiration difficulties, necessitating tracheotomy. When decanulation was possible, the vocal folds still appeared to remain in paramedian position. By voice training, the patient recovered her voice, but it remained soft and breathy. At phonation, the vocal folds made contact with each other for about half the length of the glottis, as a result of the Bernoulli effect and the elastic recoil.

Together with the improvement of the voice, the dyspnoea increased and an arytenoidectomy with partial chordectomy was indicated. The first measuring series, immediately previous to the arytenoidectomy, had been performed when the voice was slightly hoarse. The efficiency was, despite her comparatively optimal vocal poten-

Table 5-16. *Four patients, from Group III, with bilateral innervation disturbance.*

(For legends see Table 5-6.)

Patient No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB	therapy
deviant								
1		69	325	*1.59*	*0.2*	- 9.1		
9		67.5	*355*	*0.87*	*0.3*	- 7.3		arytenoidect. +
	24	51.5	*688*	*0.54*	*<0.01*	-14	- 6.7*	part. chordect.
56		79	*1039*	0.88	*1.3*	- 7.9		arytenoidect. +
	15	77.5	406	1.55	1.3	- 6.8	+ 1.1	part. chordect. (vertico-lat. displacement)
non-deviant								
23		76	217	0.92	2.9	- 2.3		arytenoidect. +
	12	69.5	*832*	*1.26*	*0.1*	-11.9	- 9.6*	part. chordect.

tialities at that moment, still low as a result of the high values for flow and subglottic pressure. The low value of I_m indicates that the dynamic vocal potentialities were small.

After the operation the patient could only whisper. On the right side a small ventral part of the vocal fold remained, the left vocal fold had an atrophic appearance and stood still in intermedian position. Consequently, a wide glottis had been achieved, and breathing difficulties disappeared.

About a year after the operation the second measuring series was carried out. The efficiency of her whispered voice had become very low: -14 dB and for I_m a value of only 51.5 dB was obtained. The dynamic range of course lies much lower than for a normal voice. The patient used much air for whispering at comparatively high values for subglottic pressure.

(In the evaluation of efficiency values one needs to take into account that the reference regression lines have been extrapolated to 51.5 dB. Real reference values for whispering in normal subjects had not been ascertained). The patient could not produce a satisfactory vocal intensity even if she tried hard. She was severely handicapped in her social relations because of her limited possibilities of speech communication.

Patient No. 56 was a woman of 47 years with a bilateral laryngeal paralysis after thyroidectomy, which had taken place one year previous to the first measuring series.

Both vocal folds stood still between paramedian and intermedian position. Despite the fairly wide glottis opening, the patient suffered from a severe dyspnoea. When speaking her voice was very breathy, and she lost much air. The patient could only speak in short phrases, her speaking rate was by nature very high and, therefore, in speaking she often became dyspnoeic. The respiratory difficulties were primarily caused by the high air flow rates at phonation, making necessary a quick inspiration in the middle of a sentence. The patient, however, was not able to widen her glottis sufficiently during quick inspiration to replenish the air supply.

On the left side, an arytenoidectomy and partial chordectomy were performed. The rest of the left true vocal fold was partially detached and diverted in craniolateral direction, then reattached close to the left ventricular fold in a variant of Langnickel's operation (Langnickel and Koburg, 1970, 1972a, b and Langnickel, 1976).

The patient soon developed a fairly normal voice, since a glottis was formed between the right ventricular fold and the fold of tissue created on the left side, thus enabling voice production. Before the operation the efficiency was low, mainly due to the high air flow rates.

At the second measuring series, after the operation, the flow values during phonation appeared to have decreased considerably. Though the subglottic pressure was much higher, the efficiency of the larynx had been raised somewhat, see Figure 5-7.

Post-operatively, the patient was very satisfied about the improvement of her voice and her respiratory possibilities.

Patient No. 23 was a man of 52 years with a bilateral laryngeal paralysis, possibly caused by a viral infection about two years previous to our first measuring series.

Because both vocal folds were fixed practically in median position, the voice sounded nearly normal. At phonation, the slackened vocal folds tightened, probably by the action of the cricothyroid muscle, moreover there was some adduction of the left vocal fold, which enabled him to close the glottis properly at phonation. As far as regression lines for flow, pressure, and efficiency are concerned, these appeared not to be deviant in the first measuring series.

Because of this configuration of the glottis, the patient suffered from severe respiratory trouble even at the slightest effort. In quiet breathing, the vocal folds moved apart by the air stream. Surgical widening of the glottis was indicated.

After the arytenoidectomy and partial chordectomy, there were no respiratory difficulties anymore. By voice training (pushing excercises) the patient recovered a hoarse voice. A glottis was formed between a hypertrophic ventricular fold at the side of the arytenoidectomy and the opposite true vocal fold. The aerodynamic data showed that voice production cost more energy. The efficiency of the larynx had decreased considerably; the flow and the subglottic pressure values had much increased.

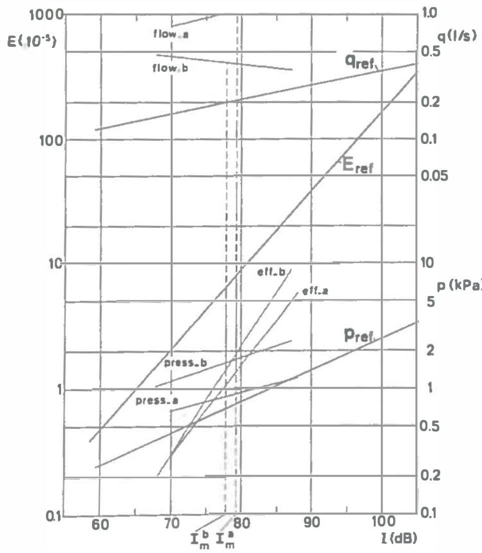


Figure 5-7.
Depiction of the regression lines for flow, pressure, and efficiency from both measuring series in Patient No. 56, represented with the corresponding reference regression lines. The data of the first measuring series have been marked with a, those of the second series with b. After an unilateral arytenoidectomy and a partial chordectomy with cranio-lateral displacement of the rest of the vocal fold, the pressure values appear to lie much higher, whereas the air consumption has decreased considerably, with no significant change in the efficiency of voice production.

The results of surgical widening

of the glottis varied with respect to the laryngeal efficiencies. In the Patients Nos. 9 and 23, the efficiency decreased very much, in Patient No. 56, this was not the case. It seems likely that the choice of the surgical procedure is an essential factor in a proper maintenance of the vocal function.

General discussion

Much information on air flow rate in the phonation of patients with laryngeal paralysis may be found in the literature. Döhne's study (1944) on air consumption in unilateral laryngeal paralysis provided the most extensive data on the subject. He found that the air consumption in phonation in his patients was much higher than in normal subjects. Döhne recorded values for air consumption in cases of severe hoarseness which were 4 to 5 times as high as normal. Even in case of slight hoarseness, the values appeared twice as high.

Many other authors, Arnold (1955a, b), Isshiki and von Leden (1964), Yanagihara and von Leden (1967), Hirano, Koike, and von Leden (1968), Koike and Hirano (1968), von Leden (1968), Iwata and von Leden (1970a, b), Iwata, von Leden, and Williams (1972), and Hippel and Mrowinski (1978), reported high air flow rates in patients with laryngeal paralysis.

The highest values have been found in patients with unilateral paralysis in which the paralysed vocal fold stood in intermedian position. Lower values were measured in unilateral paralysis with the vocal fold in paramedian or median position and in cases suffering from bilateral abduction paralysis.

Leanderson and Grape (1967) simultaneously measured the subglottic pressure and the air flow rate in one patient after chordectomy had been performed and voice lessons had been given. The subglottic pressure was measured directly by puncturing the subglottic space with a needle. They found, comparing the results with those obtained in examining a normal subject, a slightly raised air flow rate together with, what they called, a normal pressure (10.6 cmH_2O) during soft phonation. At louder phonation (a raise of 10 dB) they could not establish any increase in pressure values, whereas a double flow value was measured.

Contrary to the generally accepted idea that in laryngeal paralysis the subglottic pressure has decreased (Jeschek, 1961; Luchsinger and Arnold, 1965) it appears from our data that considerably higher subglottic pressures than those observed in normal subjects can be measured in patients with laryngeal paralysis and a deviant voice quality. There certainly is no question of lowered subglottic pressures, despite the fact that the glottis remains open at phonation. Döhne (1944) already suggested that this might possibly be the case, but experimental proof was not reported in the literature.

The high values for the subglottic pressure as found in Patient No. 9 are, of course, partly caused by the pressure p_r needed to overcome the viscous resistance. This patient used air flow rates up to 1200 ml/s. The pressure p_r will then reach a value of 0.27 kPa (2.7 cmH_2O), with a normal value for the viscous resistance. Even, when taken this value into account, the established subglottic pressure values are high. Moreover, these values are in agreement with the values found in a direct measurement by Leanderson and Grape (1967).

A high flow may be the result of a lowered tension of the affected vocal folds as well as of a higher subglottic pressure. At higher air flow rates, the Bernoulli effect has a greater influence on the medially directed movement of the vocal folds, which enables the glottis to close partly during phonation. Even if both vocal folds are fixed in paramedian position this may happen (Patient No. 9, before operation).

For practical and effective speech communication a certain sound intensity level has to be possible. Patients with laryngeal paralysis often appear able to produce this necessary intensity level, but because of the lower efficiency of the larynx, they have to exert greater effort. If a high flow has to be used the loss of air shortens the phonation time and only short sentences are possible. This leads also to very quick inspiration, which possibly leads to inspiratory stridor and breathing difficulties (Patient No. 56, before operation).

Subglottic pressures which are only a little higher than the average value in normal subjects were recorded in patients in whom dynamic closure of the glottis was possible. By stroboscopic observation, the obviously still flexible vocal folds could be seen touching each other. This was the case in Patient No. 23 during the first measuring series and in Patient No. 26 during both measuring series. In these two patients, the voice was practically normal, the flow values were not deviant either, and there was a complete dynamic closure of the glottis.

It may be concluded that there is little difference between bilateral (No. 23) or unilateral (No. 26) laryngeal paralysis as far as phonation is concerned, provided dynamic closure of the glottis is possible. In Patient No. 6, dynamic closure was impossible at low intensities. The voice, therefore, sounded breathy, but apparently a slight increase in the flow was sufficient to achieve closure of the glottis due to the Bernoulli effect. An increase in extralaryngeal and intralaryngeal muscular effort for a better glottis closure, which would have resulted in a higher subglottic pressure, is thus not necessary.

5.4.4.3 Conclusions

Summarizing, we may draw the following conclusions based on the patients from Group III:--

a. In cases of laryngeal paralysis the aerodynamic data depend on the remaining possibilities of achieving dynamic closure of the glottis. The flexibility of the vocal folds is often decisive for the possibility of dynamic glottis closure, in which case the efficiency of the voice production may be practically normal.

b. The result of a surgical widening of the glottis on the voice production seems to depend on the selected surgical procedure. The recovery of the respiratory possibilities with maximum conservation of voice function, intended by the surgical method as suggested by Langnickel, needs to be studied and discussed.

Chapter 6 Investigation conducted with trained singers

6.1 Introduction

In the last few years there has been a growing interest in investigation of the trained singing voice. The majority of studies concern the acoustic aspect of the produced vocal sound. In particular, much attention has been paid to the so-called "singing formant", and timbre and perceptual differences between the various registers (Large, 1968, 1969, 1973a, b; Large and Shipp, 1969; Sundberg, 1970, 1973, 1975, 1977; Colton, 1972, 1973a, b; Hollien, 1972, 1974; Large, Iwata, and von Leden, 1970; Seymour, 1972a, b, c; Colton and Hollien, 1973a, b; Cleveland, 1977; Murry, Singh, and Sargent, 1977).

Covering of the singing voice has been described by van Deinse (1973), van Deinse, Frateur, and Keizer (1974), and Bunch (1976).

Hirano, Koike, and Joyner (1969), Vennard, Hirano, Ohala, and Fritzell (1970a, b, 1971a, b) reported on extensive electromyographic studies of intrinsic laryngeal muscles in normal subjects, inter alios singers. Survey articles on this subject have been published in 1969 and 1970 by Hirano, Vennard, and Ohala, while Hirano in 1974 made an instructive film on the subject.

In 1968, Proctor gave a survey of the physiological basis of singing voice training. Besides, various books on the singing voice for use in singing instruction have been published (Vennard, 1967; Miller, 1977; Husler and Rodd-Marling, 1978; Seidner and Wendler, 1978).

Investigations concerning aerodynamic aspects of the singing voice have remained limited. Measurements of the air flow rate at the onset of the voice have been performed by Vennard and Isshiki (1964), Koike, Hirano, and von Leden (1967), Werner-Kukuk and von Leden (1970), Murry and Schmitke (1975), Leeper (1976), and for various voice registers: McGlone (1967, 1970), Large, Iwata, and von Leden (1970), and Large and Iwata (1971).

Simultaneous measuring of flow, directly measured subglottic pressure, and sound intensity, from which the efficiency could be calculated was performed by Rubin, LeCover, and Vennard (1967). They remarked though that "the variability of the findings among the subjects and within a single subject precluded quantitative analysis".

Bouhuys, Proctor, and Mead (1966)

Table 6-1. A survey of the subjects with a trained singing voice.

Subject No.	voice classification	nationality	
3	baritone	dutch	trained amateur singer
13	tenor	canadian	professional singer, teacher of singing
17	baritone	dutch	advanced student in singing
62	tenor	american	professional singer, teacher of singing
63	bass	german	trained singer, medical speech therapist

registered flow and indirectly measured subglottic pressure in singing. Their investigation was primarily aimed at the question of how the respiratory musculature provides the energy for phonation. Bouhuys, Mead, Proctor et al. (1968) reported on the efficiency of one trained singing voice.

In 6.2, we describe our investigations with five singers, amongst whom two singing teachers.

In 6.3, some qualitative aspects of the produced vocal sound are dealt with. In this connection we mention the occurrence of the singing formant and the vibrato, as characteristics of a well-trained singing voice. Further, a special resonance phenomenon is discussed.

The instances of phonation produced by the subjects in this part of our investigation and discussed in this Chapter may all be said to be models of what trained singers at the best of their ability may hope to achieve. Therefore, tones that would not be acceptable to the performer himself in singing a concert, were rejected on his judgement as qualitatively bad or not quite sufficient.

In producing the sung tones, the singers were somewhat hindered by the artificial elongation of the vocal tract and the fixed shape of the mouth, constrained by the mouthpiece, which sometimes indeed was experienced as uncomfortable. The use of a mask with pneumotachograph, as employed by Rubin,

Table 6-2. Table of data for flow, pressure, and efficiency derived from the regression lines from the five subjects with a trained singing voice. (For legends see Table 5-5.) In Subject No. 13, the interval between the measurements was one day, in Subject No. 62, with three measurements, two days and three days.

Subject No.	interval months	I_m dB	flow ml/s	press. kPa	effic. $x10^{-5}$	E_{rel} dB	ΔE_{rel} dB
3		81	237	0.66	11.6	0.5	
	11	82	217	0.84	12.6	0.2	- 0.3
13		87	312	1.62	14.2	- 2.4	
	0	83.5	259	1.48	8.5	- 2.4	0.0
17		82.5	253	1.1	9.2	- 1.5	
	1	81	208	1.02	8.6	- 0.8	+ 0.7
62		84.5	241	1.33	12.7	- 1.3	
	0	83.5	259	1.36	9.2	- 2.1	- 0.8
	0	86.5	245	2.02	13.0	- 2.5	- 0.4
63		77.5	195	0.49	8.5	1.4	

LeCover, and Vennard (1967) appeared to provide little subjective improvement. In 6.2, the influence of the elongated vocal tract will be further discussed.

Despite the mentioned handicaps we are convinced that the regression lines obtained are sufficiently reliable to allow to draw proper quantitative conclusions.

In one subject, some variants of the singing voice production training techniques have been investigated. The result will be discussed in 6.4; 6.5 gives conclusions.

6.2 Flow, subglottic pressure, and efficiency of phonation in trained singers

Among the normal subjects investigated and reported on in Chapter 4, there were five male subjects who had had a formal singing training or were advanced students in singing, see Table 6-1. A total of ten measuring series were carried out in these five singers, see Table 6-2.

In Subjects No. 3 and No. 17, pitches were chosen according to the system of pre-selected frequencies, in the other singers we took pitches in steps of a quarter

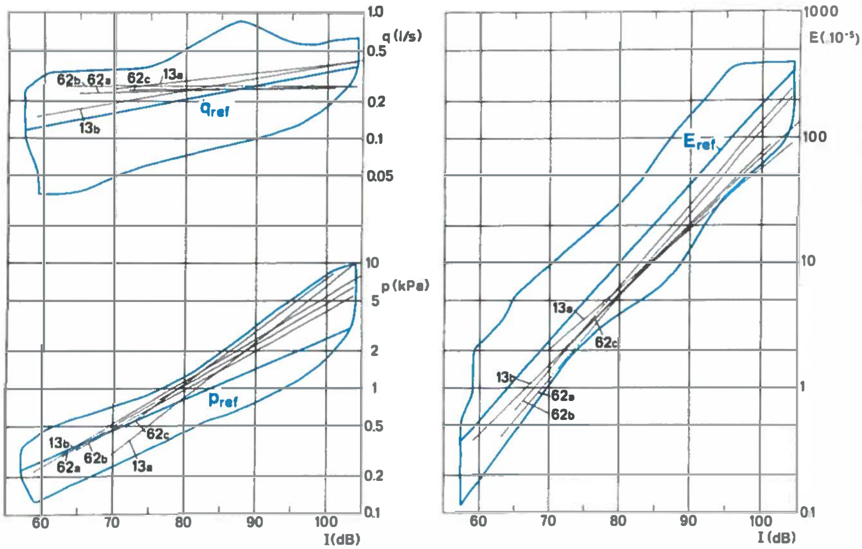


Figure 6-1. Depiction of the regression lines for flow, pressure, and efficiency from the Singers Nos. 13 and 62 (Tenor Singers). The subglottic pressures at high intensities are remarkably high, up to 10 kPa (100 cmH_2O).

in order to remain within their singing voice register. At each of the various pitches we always measured over the complete dynamic range.

The aerodynamic data of the two measuring series from Singer No. 17 have already been recorded in Figure 4-1.

In the evaluation, the aerodynamic data from the tenors impress by their high subglottic pressures and low efficiency regression lines, which lie at the limit of the relevant reference area, see Figure 6-1.

The regression lines from the other three singers lie close to the corresponding reference regression lines, see Figure 6-2. They deviate very little from those calculated from the data of non-trained voices.

From Table 6-2 appears that the relative efficiency values of the singers nearly all are more or less negative. The fact that the efficiency of the well produced singing voice is rather low, is surprising and unexpected. Generally speaking,

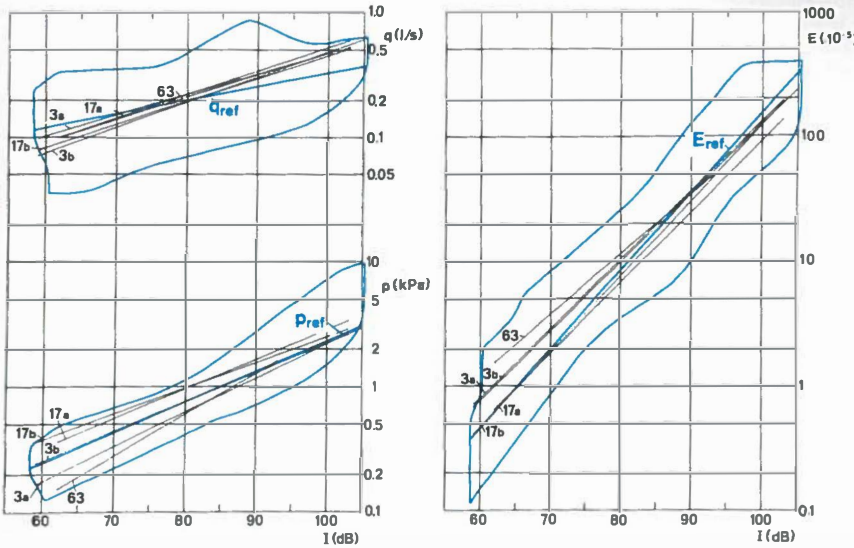


Figure 6-2. Depiction of the regression lines for flow, pressure, and efficiency from the Singers Nos. 3 and 17 (Baritone Singers) and No. 63 (Bass).

the aerodynamic data relating to intensity and pitch in singers are not different from those in non-trained voices.

Bouhuys, Mead, Proctor et al. (1968) also state that the efficiency in a well-trained amateur singer was lower than in the four non-trained singers examined at the same time. They gave no further information.

The low efficiency values in the tenor singers measured by us are due to the high subglottic pressures. High subglottic pressures (up to 70 cmH_2O) were also seen by Proctor (1968, 1974).

From our investigation, it appeared that the high subglottic pressures were used intentionally by both tenors if they sang at the high frequencies of their tessitura, in order to obtain the desired timbre, the so-called "headvoice" or as Miller (1977) indicated: "legitimate headvoice". The voice quality then has the desired "ring" (see Vennard, 1967) and is "well-balanced". The dynamic range of these good vocal quality high frequency sounds usually is not very large and lies near the maximum obtainable sound intensity.

At the lower frequencies of the tenors, when chest voice is used ("voce piena" - Miller; "full voice" - Vennard), the pressure values correspond with those of other singers and non-trained voices.

If at the high frequencies tones were produced with an unacceptable sound quality, e.g. falsetto-like or "not-balanced without ring" or "badly placed", lower pressures were measured, about 4 kPa (40 cmH_2O). This means that the larynx from an energetic point of view is used less efficiently consequently to the purpose of obtaining an optimal aesthetic sound.

The influence of the flowhead mouthpiece in the mouth and the effect of the elongation of the vocal tract by the flowhead, was studied in a separate series of experiments. For this purpose, a series of phonations was recorded in which the singers were standing and without flowhead could sing unconstrained. The oesophagus balloon had been inserted via the nose, and, from the pressure variations, the data for the subglottic pressure were ascertained according to the abrupt cessation method introduced by van den Berg (1956), see 2.7. The execution of the cessation manoeuvre caused no problem whatsoever for the trained singers and could be performed faultlessly after a short instruction. The measurements comprised an extensive dynamic range at various pitches. In this series, the tenor singers used subglottic pressures which were about equally high as those during the comparable phonations of the measuring series performed according to the standard procedure.

High intrathoracic pressures have an unavoidable influence on the circulation, as is well-known from the Valsalva manoeuvre. In phonation, especially with high subglottic pressure in tenor singers, these influences will occur. The influence of subglottic pressures on intracardiac blood pressures measured during heart catheterization has been reported by van den Berg (1956).

Subglottic pressures (intrathoracic pressures) higher than about 3 kPa (30 cmH_2O) may be expected to hinder the reflux of the blood to the heart, which influences the cardiac output. This can be ascertained inter alia by registering the changes in the peripheral circulation, e.g. in the thumb, by a photoplethysmographic method. To a thumb of Tenor Singer No. 13 a transducer was fastened (Vasotest, Groningen University Laboratory for Medical Physics) and thus the fluctuations in the circulation were registered, together with the sound signal (Brüel and Kjaer apparatus) on the Mingograph recorder.

The result is represented in Figure 6-3; in the upper part (A) are the curves of sound intensity, air flow rate, oesophageal pressure, and lung volume; in the lower part (B), from a corresponding phonation, the photoplethysmogram and the sound signal. The arm muscles were relaxed. From this figure it appears that the amplitude of the vascular pulsations in the thumb decreases very much during the phonation and increases after the phonation has finished, as a sign of so-called reactive hyperaemia following the release. In case of such high subglottic pressures venous congestion of blood in the head also developes.

In a few measuring series, in which high subglottic pressures were also produced, the thumb-plethysmogram was recorded simultaneously with the aerodynamic measurements. The influence on the peripheral circulation was not always so unambiguous and distinct as in Figure 6-3. There certainly are many opportunities for further study of this matter in general.

In the daily performance of the professional singer, high subglottic pressures, which might supposedly be injurious to the larynx, in fact do not often occur, because, as already mentioned, these do occur only in loudly sung high tones. Phonations at the same pitch, which are to be produced softly, can be sung with much lower subglottic pressure. If in singing, a less heavy voice register ("voce finta" - Miller, 1977) is used the influence on the blood circulation is also less or even absent.

From measurements and from the information provided by the singers, we received the impression that in singing provisions are made that the air flow remains within certain individually determined limits in order to protect the larynx from injury.

It is remarkable that in three measuring series from Tenor Singer No. 62 the air flow rate is nearly independent of the intensity. The great reproducibility is also conspicious. The other singers indeed do use at lower intensities a lower flow. The relation between flow

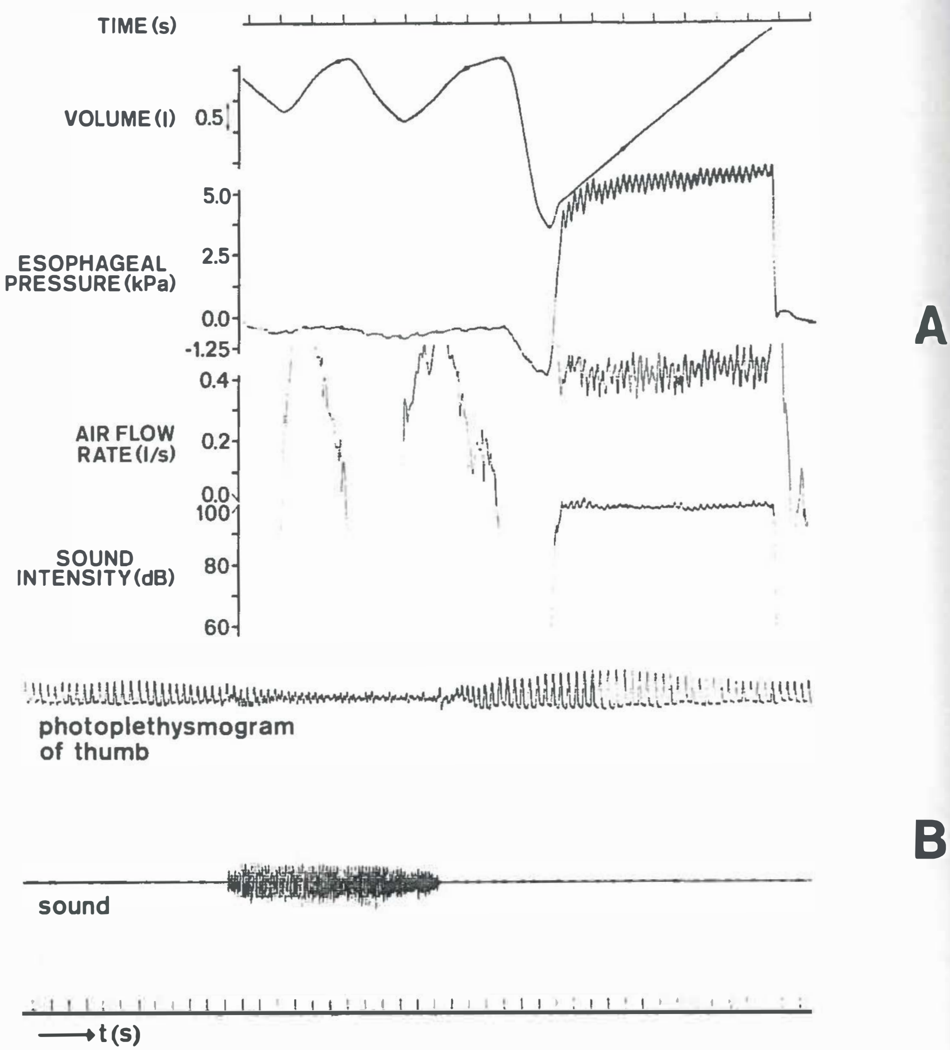


Figure 6-3(A,B). The influence of high subglottic pressure on peripheral circulation:

A. A simultaneous registration of lung volume, oesophageal pressure, air flow rate, and sound intensity of one phonation at 440 Hz from a professional Tenor, (No. 13).

and intensity seems to be determined individually, as is the relation between subglottic pressure and intensity, and to be connected with individual differences in the build of the larynx.

6.3 Qualitative aspects of the singing voice

The quality of the produced tone in singers is of decisive significance. From various investigations it appears that a well produced tone has certain properties. In that context the vibrato and the mutual relation of the overtones seem to be the most important factors (Winckel, 1952, 1953; Vennard, 1967, and Sundberg, 1970, 1977). These characteristics can be shown by frequency analysis of the produced tones. We study a few tones this way and give an example in 6.3.1.

The sound which ultimately comes out of the mouth is modelled by the vocal tract. The form of the vocal tract determines which vowel will be produced. However, the vocal tract and the glottis generator (larynx) influence each other mutually, which under certain circumstances leads to a special phenomenon which will be extensively dealt with in 6.3.2.

6.3.1 Quality of the sung tones; vibrato and the singing formant

A good sung tone appeared to go along with the presence of a regular vibrato and the existence of harmonic overtones at about 2500-3500 Hz, see Figure 6-4. Vennard (1967) named the qualitative characteristics of a good tone "ring". Winckel (1952, 1953) and Sunberg (1970) used the term "singing formant".

The sonagram of Figure 6-4A shows the same pattern as the sonagrams derived from well-produced tones described in the literature (van den Berg and Vennard, 1959;

B. A photoplethysmogram of the thumb, with relaxed arms, taken while the subject was phonating, presented with a simultaneous sound registration of the phonation produced under identical conditions as in A. From the plethysmogram follows that the heart, because of the high intrathoracic pressure, can only keep the circulation going at the cost of considerable strain.

Vennard, 1967; Large, 1973b). For comparison, Figure 6-4B shows the sonagram of a non-trained Subject (No. 2) who at the same pitch and sound intensity produced an identical vowel transition. Obviously the singing formant is missing, whereas in the sonagram of the untrained person more upper partials are recorded.

An irregular vibrato or the lack of it indicated that the singers produced the tone badly. The presence of the vibrato is not only visible in the sonagram, but also can be read from the curves for flow, pressure, and intensity (see Figures 6-3 and 6-5).

6.3.2 Acoustic coupling of vocal tract and larynx

As already mentioned in Chapter 2, some normal subjects appeared to experience difficulties in phonation at about 300 Hz. These often consisted of difficulties in maintaining exactly the required pitch or in producing desired voice quality at a given pitch. Occasionally these difficulties were so severe, that at certain notes the voice skipped into another unintended register.

These difficulties are the consequence of the artificial elongation on the natural vocal tract (pharynx and oral cavity) by the mouthpiece with fluid receptacle and flowhead. By this elongation, all the formants will be depressed in frequency and this yields a greater chance that one of the lower harmonics coincides exactly with a formant resonance peak and is considerably amplified. The measured intensity value may therefore be larger. Isshiki (1964) pointed this out and the effect was already mentioned in the discussion of Figure 4-2.

In the natural vocal tract the coupling of the vocal tract and the larynx and the influence of the acoustic impedance and damping factors do not cause a hindrance in speaking and singing (van den Berg, 1953, 1961). At phonation with an elongated vocal tract these problems have to be faced, though, as proved already by Weiss's experiments (1932a, b). Van den Berg explained this phenomenon in 1954. In special cases the effect can be so great that the fundamental tone is influenced, i.e. takes a somewhat different frequency.

Because in our experiments the elongation of the vocal tract amounts to 16 cm, a direct influence on the fundamental tone of male subjects is practically

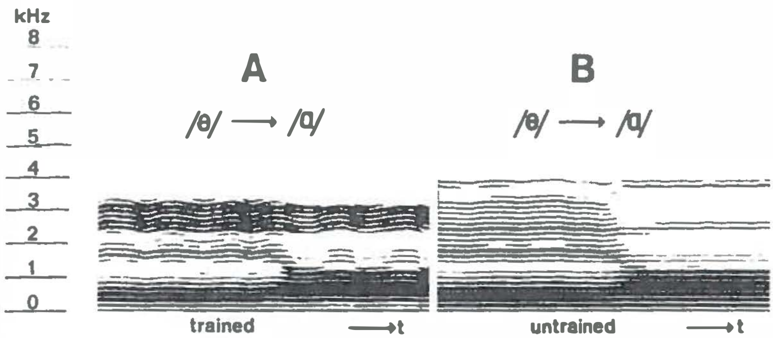


Figure 6-4(A,B). Sonagrams of a trained voice (A) and a non-trained voice (B); (Sona-Graph Kay Elemetrics Corp. type 6061-B). Phonation took place at moderate sound intensity at a pitch of E3 (165 Hz). Both subjects made a vowel transition from the vowel /e/ to the vowel /a/. The formant shifts are identical in both subjects. The vibrato in the trained singing voice is clearly visible as the wave like movements and the "singing formant" as the dark band in the spectrum at about 2700 Hz, which remains unaltered even when the vowel has changed.

out of the question. It is possible though that one of the lowest overtones may coincide with the lowest formant.

Because of the unavoidable acoustic influence, the changes of the sound due to the elongation of the vocal tract and the fixation of the mouth orifice, the singer was deprived of the use of a number of professional adaptations with respect to vocal tract and oral orifice. According to the subjective critical remarks of the participants themselves, these limitations seemed to be of greater importance in lower singing voices than in higher voices.

The place and strength of the resonance of the additional vocal tract were studied by fitting it to an Artificial Mouth (Brüel and Kjaer, type 4219), activated by a Beat Frequency Oscillator (Brüel and Kjaer, type 1022). With this measuring set the frequency characteristic was measured from 100 Hz to 10 kHz. The first two resonances were measured at 730 Hz and 1400 Hz respectively. Moreover, a sharp antiresonance was ascertained at about 2000 Hz.

In phonation with an elongated vocal tract the tuning can be altered by small changes in the vocal cavities, e.g. by a relaxation of the walls of oral or pharyngeal cavity, or a slight shift of the tongue and this may loosen the coupling between elongated vocal tract and larynx. In that case the glottis generator maintains the desired adjustment without difficulty. In normal phonation the adaptations of the position of the larynx and the vocal cavities are of great importance for the singer, as the studies of Sundberg (1970, 1977) have shown. A great part of the training time of a singer is devoted to learning to make these adaptations (Registerausgleich and Vokalausgleich).

The intensity variations by making a slow glissando with the additional vocal tract fitted to the natural vocal tract, and trying to maintain the subglottic pressure at the same level (subjectively), amounted to about $\pm$ 3.5 dB. The greatest sound amplification took place at a fundamental frequency of about 310 Hz, i.e. at about the lowest formant of the elongated system.

It is not surprising that especially singers experience difficulties at certain frequencies and qualities of tone, in view of their striving for perfection.

In Tenor Singer No. 13, the requirement to produce a tone with a specific quality ("ring") at an extremely high fundamental frequency and a very high intensity led to a critical situation, in which it became possible for this coupling phenomenon to occur. During the phonation, the registered sound intensity suddenly increased by 10 dB, whereas no changes took place in flow and pressure values, see Figure 6-5. The singer remarked that he felt at a certain moment a sensation as if his larynx was no longer under his control anymore.

It is likely that such a phenomenon can occur only if a number of factors coincide. This may explain why these extreme problems only occurred in one of our subjects under unusual conditions and were not observed to this extent in any other subject, or could be avoided by them with a somewhat different adjustment of the larynx or vocal tract. The influences on the measured aerodynamic relations will be small in general and go lost in the intra-individual spreading.

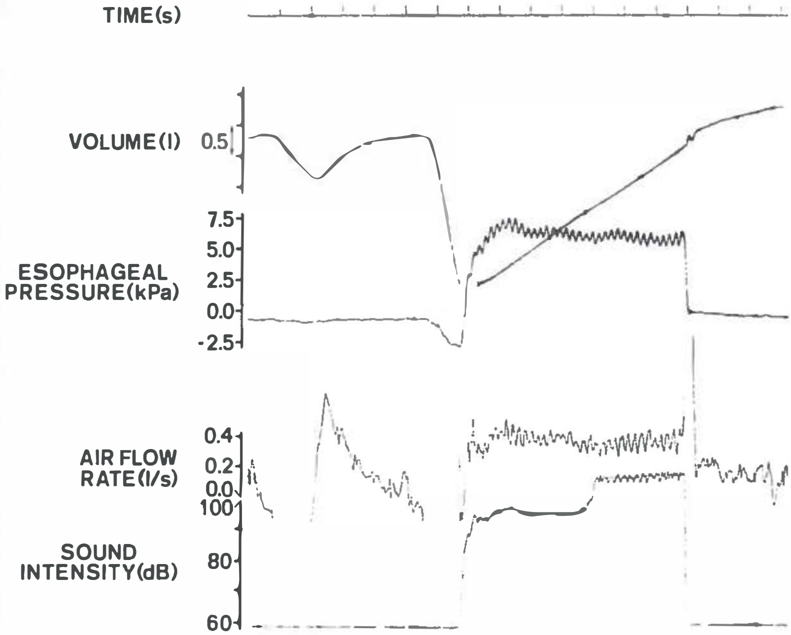


Figure 6-5. Simultaneous registration of lung volume, oesophageal pressure, air flow rate, and sound intensity of one phonation at 420 Hz on the vowel /a/ from a professional Tenor, No. 13. About 3.5 seconds after the onset of the phonation, a sound intensity increase of about 10 dB was registered in consequence of the resonance phenomenon, discussed in the text.
The values of the subglottic pressure and the air flow rate did not change. The regular variations of the oesophageal pressure curve correspond with the vibrato.

6.4 Variants of the singing voice production

Rubin, LeCover, and Vennard stated in 1967, "An artistic singing tone is one presumably physiologically and acoustically optimally produced. It contrasts with tones more frequently heard which are colored by various undesirable qualities such as breathiness, constriction, throatiness, ect."

The same authors described some qualitative aerodynamic aspects of these aberrant phonations, differing from optimal vocal tones. Such variants of voice production have also been investigated, in 1959, Vennard acting as subject, by sonagraphy combined with radiography of the pharyngeal and oral cavities, in order to ascertain the changes of the laryngeal position and the vocal tract (van den Berg and Vennard, 1959; Vennard, 1967).

In the same subject (among others) consciously produced variants of voice production were investigated by transcutaneous electromyography of a number of laryngeal muscles, as well as some palatal muscles (Vennard, Hirano, Ohala, and Fritzell, 1970a,b, 1971a,b).

In 1978, van Deinse and Goslings produced a scientific video-film on the changes in the vocal tract in various singing techniques. For this purpose they used sideways taken X-ray pictures.

Systematical examination and registration of the values of the subglottic pressure and flow was reported not to be possible in the aforementioned study of Rubin, LeCover, and Vennard (1967), because of the great inter-individual and intra-individual dispersion of the data. In Chapter 4, we demonstrated that an intra-individual comparison can be made in a reliable way if the results are compared with the normal regression lines of the same subject.

In Singer No. 63 (Bass), the regression lines were calculated from 82 phonations. After the normal series, some variants of the singing voice production were also investigated, see Figure 6-6.

The various singing techniques presented here show in the extreme variants some clear differences with respect to pressure and flow. As far as the subglottic pressure is concerned, we established a deviant pattern in singing according to the so-called "Stauprinzip". The higher subglottic pressures though are accompanied by low flow values, with the consequence that the efficiency does not deviate.

This "Stauprinzip" technique of singing was propagated by Armin (1909) but has been rejected generally, because it may lead to damage of the voice. Moreover, the method can only be used in a limited way (Seidner and Wendler, 1978). Extensive investigations on the "Stauprinzip" have been made more than 50 years ago by Schilling (1922).

In the tenor singers we found

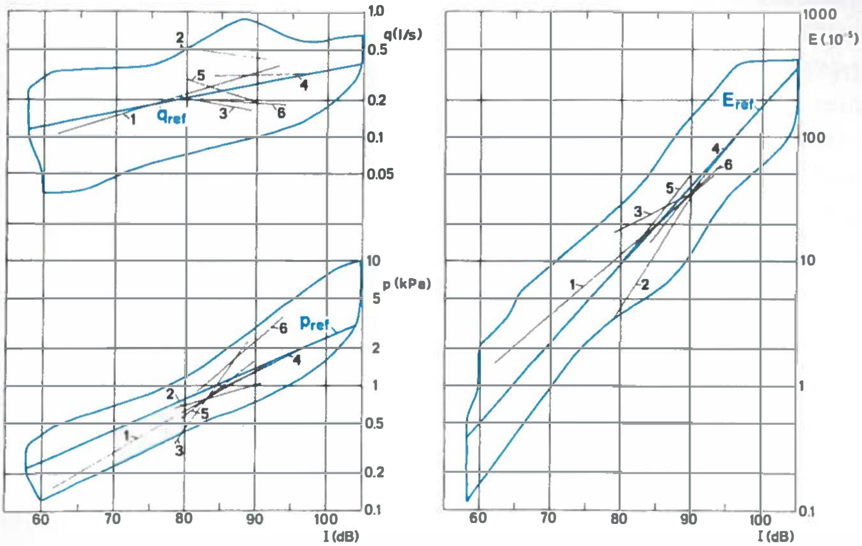


Figure 6-6. Depiction of the regression lines for flow, pressure, and efficiency from the Singer No. 63 (Bass). The regression lines from the normal measuring series (1), are distinguished by ciphers from the regression lines obtained from the use of various singing voice techniques: (2) "verhauchte Einsätze", (3) "falsche Atemtechnik", (4) "maximale Rachenweite", (5) "Nasalieren", (6) "Stauen".

very high subglottic pressures, but without further investigation, this is no sufficient reason to discard this singing method completely. For the moment, we agree with Schilling's conclusion: "Wenn ich trotz der offensichtlichen Gefahren das Stauen, ebenso wie Froeschels nicht vollständig verwerfe, sondern ihm eine berechtigte Stellung in der Gesangspädagogik einräume, so geschieht es deshalb, weil ich glaube, dasz durch vorsichtige und allmählich gesteigerte Stauübung, die Kraft und Leistungsfähigkeit der für die dynamisch maximal gesteigerte Phonation in Aktion tretenden antagonistischen Atemmuskulatur gestählt und durch richtige koordinative Einstellung der übrigen Stimmuskulatur (Entspannung der Hals- und Kehlkopfmuskels) die Gefahren welche grosze stimmliche Anstrengungen bei ungenügend trainierter und unökonomisch eingestellter Atem- und

Stimmuskulatur mit sich bringen, eher vermieden werden können."

In Figure 6-6, we observe a decrease of the air consumption as a consequence of the so-called "Nasalierungsprinzip" (inter alios Pahn, 1964, 1966) by raising the intensity. Because the pressure values do not deviate from the average, the phonations with higher intensities are more efficient since the air flow decreases. In phonations with a breathy attack (verhauchte Einsätze), especially at lower intensities, high air flow rates were measured, for the lowest intensities, even outside the reference area for the flow. The efficiencies of these phonations were accordingly low.

6.5 Conclusions

a. The efficiency of aesthetically good phonations at high sound levels produced by trained singers in general is lower than that of phonations produced by non-trained voices. The efficiency of the voice seems to be secondary to the desired quality of the voice.

b. In tenor singers, loud phonations in the upper compass of the voice may go along with very high subglottic pressures, which have an evident influence on the blood circulation.

c. Under exceptional circumstances the function of the larynx may be influenced by the acoustic properties of the artificially elongated vocal tract coupled to it.

d. Variants in singing voice technique, according to various teaching methods, show up in the aerodynamic data.

Chapter 7 Summary

We investigated the efficiency and other aerodynamic aspects of voice production in normal and abnormal larynxes.

In Chapter 1, a short survey is given of the myoelastic-aerodynamic theory of voice production, briefly discussing the importance of air flow rate and subglottic pressure.

By relating the power necessary for sound production to the produced sound intensity, the efficiency of the laryngeal generator can be ascertained. The purpose of our study was to establish to which degree the efficiency in various laryngeal disturbances will be influenced and to formulate criteria for predicting and evaluating the result on efficiency of therapeutic measures in our patients. Data obtained in normal subjects without vocal complaints have been used for comparison.

In Chapter 2, the methods employed for measuring sound intensity, air flow rate, and subglottic pressure at various pitches and sound intensities over the total vocal compass have been described.

The sound intensity is measured by a microphone and the air flow rate by pneumotachography.

For measuring the subglottic pressure we used an indirect method. The subglottic pressure was ascertained from the changes in the oesophageal pressure during and/or after phonation. The pressure in the oesophagus also varies with varying lung volume, so we had to take this latter into account in the determination of subglottic pressure from measurements of the oesophageal pressure. The changing lung volume was ascertained by integration of the flow signal from the pneumotachograph.

In the registration of volume curves, we had to correct for various differences in the physical properties of inspired and expired air. This is theoretically explained and illustrated by analytical experiments.

Generally, pressure changes due to the viscous resistance of the lungs and airways are low during phonation.

By applying a second correction method, it was possible to compensate automatically the changes in the oesophageal pressure due to changes in the lung volume during the measuring series. Thus the subglottic pressure could be read directly from the corrected oesophageal pressure curve.

The indirect measurement of the

subglottic pressure was verified by simultaneous direct measurements in three patients.

In Chapter 3, the analysis of the curves and the accuracy of the measurements are discussed.

Reduction of the experimental data from single phonations took place by calculating regression lines through the measuring points. These regression lines apply to the relation between a) the intensity and b) respectively, the air flow rate, the subglottic pressure, or the efficiency.

The regression lines were used to obtain average values and characteristic values for each subject.

Chapter 4 gives the results obtained with normal subjects without vocal complaints. We started with 4267 phonations from 63 subjects in 93 measuring series. However, some phonations were assessed by trained listeners as acoustically deviant. The remaining data from 2736 well-sounding phonations, obtained in 72 measuring series in 24 males and 21 females, were used to establish reference values and reference areas for the evaluation of data from patients.

The pitch of the phonations appeared to have little influence on the course of the regression line. The data for all pitches in one measuring series therefore were converted into regression lines, the intensity being considered as independent variable.

The flow and pressure values and, therefore, also the efficiency values, showed a great inter-individual spread. Reproducibility measurements showed that the intra-individual differences are much smaller than the inter-individual differences and that a good reproducibility exists.

By statistical evaluation of the measurements in the same normal subject, reliability intervals were calculated, enabling us to establish the significance of therapeutic results in patients.

The averages of the regression coefficients of the regression lines of all normal subjects were used to ascertain reference regression lines for flow, pressure, and efficiency. By referring the measured efficiency to the reference efficiency line, a relative measure of efficiency was obtained, which enabled us to establish the efficiency of a given individual larynx.

The set of regression lines was used to obtain reference areas representing the distribution spread of normal values. Later analysis of deviant sounding phonations proved that the aerodynamic data of these phonations lay for the greater part within the reference areas.

Intentionally produced hoarse phonations, from normal subjects appeared to deviate clearly from "normal" aerodynamic values of the same subject.

As the intra-individual differences are much smaller than the inter-individual differences, we concluded that a patient or a normal subject may serve as a standard for himself, to ascertain changes in the aerodynamic pattern, e.g. as the result of treatment.

The obtained measuring results were compared with data from the literature.

Chapter 5 gives the results obtained in 64 patients in 120 measuring series comprising 4983 phonations.

The patients showed a great variety of laryngeal disturbances. They were divided into three main groups: Group I, patients having organic disturbances of the vocal folds, Group II, patients having normal vocal folds and, in most cases, slight adduction disturbances, i.e. patients with "functional voice disorders", and Group III, patients having normal vocal folds, but with severe innervation disturbances of the laryngeal muscles.

From each group, the cases of some interesting patients are discussed in detail.

The data of the first measuring series were used to ascertain the diagnostic value of the aerodynamic data: flow and subglottic pressure, alone or in combination (efficiency).

The great inter-individual dispersion in patients with seemingly the same laryngeal disturbance, depreciates the value of single data. It appears that a specific aerodynamic pattern for a certain laryngeal disturbance does not exist. This also means that a single measurement can hardly establish the diagnosis of a vocal disturbance. However, since it yields a rough impression about the functioning of the larynx it may reveal a hyperfunctional use, as we see from the fact that the subglottic pressure regression lines from all patients were found to lie higher than the pressure reference line and in 59% of the cases to lie outside the reference area.

In Group I (organic disturbances),

in about 30% of the patients no aerodynamic disturbances were diagnosed. This was the case with patients with slight vocal fold affections like hyperaemia or oedema, or some patients with the clinical diagnosis of nodules. In more severe disturbances, obviously deviating aerodynamic values were measured.

The subglottic pressure values lay in general too high, the flow values were much dispersed. The efficiency was about 1 to 6 dB lower than the reference value, with one highly deviating value of -13.5 dB.

It was remarkable that it made little difference in the efficiency whether the vocal fold affection consisted of local disturbances like nodules, polyps, cysts, or papillomas, or of more extensive disturbances of the surface of the folds. The possibility of (dynamic) glottis closure appeared to be of great importance.

In Group II (functional disturbances), in nearly all patients an incomplete closure of the glottis was ascertained. Despite these incomplete glottis closures, the flow values appeared to be deviant in only two cases, whereas the subglottic pressures in most cases appeared to be too high. The efficiency lay roughly about 4 dB lower than the reference value. Most patients in this group received voice training.

With respect to the patients of Group III (severe innervation disturbances) a survey has been given of the clinical aspects of unilateral or bilateral laryngeal paralysis. In three patients with a bilateral paralysis surgical widening of the glottis was necessary because of respiratory difficulties. The effect of the operation on the efficiency and on possibilities of communication is discussed.
In this group the efficiency in patients in whom no static closure of the glottis was effectuated, was about 8 dB lower than the reference value. The subglottic pressure in this group appeared to be, despite the paralysis, remarkably high.

In 47 patients, a second measuring series was performed, after some form of medical (surgical) therapy and/or voice training had been given.

A number of these patients were examined several times, in a total of 56 measuring series after therapy, 2434 phonations were obtained.

The efficacy of therapeutic measures, derived from the difference of the relative efficiency values, appeared to be favourable in most patients, though the relative efficiency values nearly always remained negative.

In the patients in whom even after treatment complete (dynamic) glottis closure was still impossible, e.g. by a persisting chink, an improvement of the efficiency appeared to be related to a more relaxed phonatory pattern. In aerodynamic terms, this was related to the decrease of the subglottic pressure. To what extent the flow values were changed depended mainly on the possibility of a dynamic closure of the glottis.

In Chapter 6, we discuss the results of investigations with five trained singing voices.

The efficiency was compared with that of non-trained voices. We concluded that the singers produced the sound in such a way that the efficiency was of secondary importance to the aesthetic demands.

These qualitative demands, especially in the tenor singers led to the appearance of very high subglottic pressures at high sound intensities. The influence of these very high subglottic pressures on the blood circulation is indicated and demonstrated by photoplethysmography. Some qualitative aspects like vibrato and the presence of the singing formant were studied.

The acoustic coupling of the vocal tract to the larynx is discussed with respect to the occurrence of a particular resonance phenomenon.

The chapter closes with a discussion of aerodynamic aspects of some variants of the singing voice production, based on various pedagogic techniques. The efficiency appeared to differ little in these variants, though difficulties with respect to flow and pressure values could be demonstrated. Our conclusion was that in these variants of the singing voice production the subjective and singing pedagogic aspects are of greater importance than the aerodynamic ones.

Samenvatting

In dit onderzoek worden de efficiency van de stemvorming en de bij de stemvorming optredende aërodynamische verschijnselen bij normale en afwijkende strottenhoofden besproken.

In Hoofdstuk 1 wordt een kort overzicht gegeven van de wijze waarop volgens de myoelastische-aërodynamische theorie het stemgeluid tot stand komt. De betekenis van de luchtstroomsterkte (flow) en de subglottische druk wordt beknopt besproken.

Door de energie, die nodig is voor de stemvorming, in verband te brengen met de geproduceerde geluidsenergie, wordt de efficiency bepaald.

Het doel van het onderzoek was na te gaan in welke mate de efficiency door verschillende larynxaandoeningen wordt beïnvloed en wat het effect is van stemtherapeutische maatregelen bij patiënten. Ter vergelijking dienen gegevens die op dezelfde wijze verkregen werden bij proefpersonen zonder stemklachten.

In Hoofdstuk 2 worden de gebruikte methoden beschreven voor het meten van de geluidssterkte, de flow en de subglottische druk bij verschillende toonhoogten en geluidssterkten over de gehele stemomvang.

De geluidssterkte wordt gemeten met een microfoon, de flow met een pneumotachograaf.

Voor het meten van de subglottische druk wordt een indirecte meetmethode gebruikt. Daarbij wordt uit de verandering van de oesophagusdruk bij het foneren de subglottische druk bepaald. De druk in de slokdarm variëert tijdens de ademhaling in afhankelijkheid van het longvolume. Om de subglottische druk betrouwbaar te kunnen meten moet daarom rekening worden gehouden met het longvolume. De veranderingen van het longvolume worden geregistreerd door integratie van het flowsignaal.

Bij de registratie van de volumecurve wordt gecompenseerd voor de verschillen in fysische eigenschappen van in- en uitademingslucht. Deze correctiemethode wordt zowel theoretisch als experimenteel geanalyseerd en toegelicht.

Drukveranderingen als gevolg van de visceuze weerstand van de longen en de luchtwegen zijn in het algemeen klein tijdens de fonatie.

Door een tweede correctiemethode toe te passen wordt het mogelijk reeds tijdens de metingen voor de met het longvolume samenhangende veranderingen te compenseren. Hier-

door kan de subglottische druk direct uit de gecorrigeerde oesophagusdrukcurve worden afgelezen.

Het indirect bepalen van de subglottische druk werd geverifiëerd door gelijktijdig uitgevoerde directe metingen bij een drietal patiënten.

In Hoofdstuk 3 wordt het analyseren van de curven besproken en wordt nagegaan met welke meetnauwkeurigheid de aërodynamische gegevens en de efficiency kunnen worden bepaald.

Reductie van de meetgegevens van de afzonderlijke fonaties vindt plaats door het berekenen van regressielijnen door de meetpunten. Deze regressielijnen geven het verband aan tussen a) de intensiteit en b) de flow, de subglottische druk respectievelijk de efficiency.

De regressielijnen worden verder in het onderzoek gebruikt als gemiddelde waarden voor de meetgegevens van iedere persoon; bovendien worden hieruit kenwaarden afgeleid.

De hoofdzaken van de presentatie van de meetresultaten in grafieken en tabellen worden met enkele voorbeelden toegelicht.

In Hoofdstuk 4 worden de resultaten beschreven van 4267 fonaties door 63 normale proefpersonen zonder stemklachten, in 93 meetseries. Een deel van de fonaties is door getrainde luisteraars als akoestisch afwijkend beoordeeld. De resterende gegevens van 2736 goed klinkende fonaties, verkregen in 72 meetseries bij 24 mannen en 21 vrouwen, zijn gebruikt voor het vaststellen van referentiewaarden en referentiegebieden voor het beoordelen van patiëntengegevens.

De toonhoogte van de fonaties blijkt van weinig invloed te zijn op het verloop van de regressielijn. De meetgegevens worden daarom per complete meetserie herleid tot regressielijnen, waarbij de intensiteit als onafhankelijke variabele wordt beschouwd.

De flow- en drukwaarden, en dientengevolge ook de efficiencywaarden tonen een grote inter-individuele spreiding. Uit reproduceerbaarheidsmetingen blijkt dat de intra-individuele verschillen veel geringer zijn en dat een goede reproduceerbaarheid bestaat.

Door statistische bewerking van metingen bij dezelfde proefpersonen werden betrouwbaarheidsintervallen vastgesteld, waarmee het significant zijn van het therapieresultaat bij patiënten kan worden afgelezen.

Uit de gemiddelde waarden van de regressiecoëfficiënten van de afzonderlijke regressielijnen van de proefpersonen werden referentie-regressielijnen bepaald voor de flow, de druk en de efficiency. Door de gemeten efficiency te vergelijken met de referentie-efficiencywaarde wordt een relatieve efficiency-maat verkregen, waarmee de efficiency van een bepaalde larynx wordt vastgelegd.

De verzamelingen van de regressielijnen van de proefpersonen werden gebruikt voor het vaststellen van referentiegebieden voor de flow, de druk en de efficiency.

Analyse van de aërodynamische gegevens van afwijkend klinkende fonaties wees uit, dat deze in de meeste gevallen binnen de referentiegebieden lagen.

Bewust afwijkend geproduceerde fonaties door proefpersonen blijken in aërodynamisch opzicht duidelijk af te wijken van de "normaal" waarden van dezelfde proefpersonen.

Mede omdat de intra-individuele verschillen veel geringer zijn dan de inter-individuele verschillen, wordt de conclusie getrokken dat een patiënt of proefpersoon als norm kan dienen voor zichzelf, om veranderingen in het aërodynamisch patroon, b.v. als gevolg van een therapeutische maatregel, vast te leggen.

De verkregen meetresultaten worden vergeleken met de in de literatuur vermelde gegevens.

In Hoofdstuk 5 worden de resultaten besproken, die verkregen werden bij 64 patiënten in 120 meetseries met in totaal 4983 fonaties.

De patiënten vertoonden een grote variatie aan larynxaandoeningen en werden verdeeld in drie hoofdgroepen: Groep I, patiënten met organische afwijkingen aan de stemplooien; Groep II, patiënten met gave stemplooien en, in de meeste gevallen, lichte adductiestoornissen, d.w.z. patiënten met "functionele stemstoornissen" en Groep III, patiënten met gave stemplooien, maar met ernstige innervatiestoornissen. Van iedere groep worden enkele patiënten nader besproken.

De gegevens van de eerste meetserie bij deze patiënten worden gebruikt voor het vaststellen van de diagnostische waarde van het meten van aërodynamische gegevens als flow en subglottische druk afzonderlijk of in combinatie, zoals tot uitdrukking komt in de efficiencywaarde.

De grote inter-individuele spreiding in de meetgegevens van proefpersonen respectievelijk patiënten met ogenschijnlijk dezelfde larynxaandoening, maakt de diagnostische waarde van geïsoleerde metingen gering. Er blijkt geen specifiek aërodynamisch patroon te bestaan voor een bepaalde larynxaandoening. Het eenmalig meten van de aërodynamische gegevens levert nauwelijks een bijdrage tot de diagnostiek van stemstoornissen. Het kan echter wel een globale indruk geven over de werking van de larynx. De regressielijnen voor de subglottische druk blijken bij alle patiënten hoger te liggen dan de druk referentie-regressielijn en in 59% van de gevallen buiten de referentiegebieden te liggen.

In Groep I (organische stoornissen) werden bij ca 30% van de patiënten geen afwijkingen in aërodynamisch opzicht vastgesteld. Het betreft dan patiënten met klinisch niet-ernstige stemplooiaandoeningen als hyperaemie of oedeem en een deel van de patiënten met de klinische diagnose stemplooiknobbels. Bij de meer ernstige aandoeningen worden in aërodynamisch opzicht wel duidelijk afwijkende waarden gemeten.

De subglottische drukwaarden liggen in het algemeen hoog, de flowwaarden lopen sterk uiteen. De efficiency bleek ca 1 dB tot 6 dB lager te liggen dan de referentiewaarde, met een uitschieter van -13,5 dB.

Het is opmerkelijk dat het voor de efficiency niet veel verschil maakt of de stemplooiaandoening bestaat uit plaatselijke afwijkingen als stemplooiknobbels, poliepen, cysten of papillomen of uit meer uitgebreide afwijkingen van het stemplooioppervlak. Van groot belang blijkt de mogelijkheid tot dynamische glottissluiting.

In Groep II ("functionele stemstoornissen") werd bij bijna alle patiënten een onvolledige sluiting van de glottis vastgesteld. Het is evenwel opvallend, dat desondanks de flowwaarden slechts in twee gevallen afwijkend zijn, terwijl de subglottische drukwaarden meestal te hoog zijn. Een mogelijke verklaring hiervan wordt besproken.

De efficiency ligt globaal ca 4 dB lager dan de referentiewaarde.

Voor de bespreking van de patiënten uit Groep III wordt eerst een overzicht gegeven van de klinische aspecten van enkelzijdige en dubbelzijdige larynxverlammingen.

Bij drie patiënten met een

dubbelzijdige verlamming bleek in verband met ademproblematiek een glottisverwijdende operatie noodzakelijk. Het effect van de operaties op de efficiency en op de communicatiemogelijkheden wordt besproken.

Bij de patiënten in deze groep, waarbij geen totale (dynamische) glottissluiting tot stand kwam, was de efficiency ca 8 dB lager dan de referentiewaarde. De subglottische drukken blijken bij deze groep, ondanks de verlamming, opmerkelijk hoog.

Bij 47 patiënten is ook een meetserie gedaan, nadat een vorm van medische (chirurgische) en/of logopedische therapie was gegeven. Een aantal patiënten is vaker onderzocht, in totaal zijn 56 meetseries na therapie opgenomen, met in totaal 2434 fonaties.

De invloed van therapeutische maatregelen, afgeleid uit het verschil van relatieve efficiencywaarden, blijkt bij de meeste patiënten gunstig, hoewel de relatieve efficiencywaarden vrijwel altijd nog negatief zijn.

Bij patiënten waarbij ook na therapie geen totale (dynamische) glottissluiting mogelijk is, b.v. door een aan de dorsale zijde openblijvende glottis, blijkt een verbetering van de efficiency samen te hangen met een meer ontspannen foneren. Dit blijkt in aërodynamische termen samen te hangen met het dalen van de subglottische druk. In hoeverre de flowwaarden dalen hangt vooral samen met de mogelijkheden tot dynamische glottissluiting en de grootte van de subglottische druk.

In Hoofdstuk 6 wordt het resultaat besproken van onderzoekingen bij vijf getrainde zangers. De efficiency wordt daarbij vergeleken met die van niet-getrainde stemmen.

Het blijkt dat de efficiency van de stemvorming door de zangers ondergeschikt gemaakt wordt aan de esthetische eisen aan de gezongen toon.

Deze kwalitatieve eisen blijken met name bij de twee zangers-tenoren te kunnen leiden tot het optreden van (zeer) hoge subglottische drukken. De invloed van deze hoge subglottische drukken op de bloedcirculatie wordt nagegaan door fotoplethysmografisch onderzoek van de bloeddoorstroming in een duim.

Enkele kwalitatieve aspecten van een goede zangtoon, zoals de aanwezigheid van vibrato en van de zg. zangformant, worden besproken.

De akoestische koppeling van het aanzetstuk en de larynx wordt aan de hand van het optreden van een resonantiefenomeen besproken.

Het hoofdstuk wordt besloten met het bespreken van aërodynamische aspecten van varianten van de zangstemvorming, die in het algemeen berusten op verschillen in zangpedagogische technieken. De efficiency blijkt bij deze varianten weinig te verschillen, hoewel verschillen in de flow- en drukwaarden wel aantoonbaar zijn. Vastgesteld wordt dat bij deze varianten van de zangstemvorming de subjectieve en zangpedagogische aspecten van groter belang zijn dan de aërodynamische.

References

Armin, G. (1909): Das Stauprinzip. Bongard, Strassburg.

Armore, S.J. (1967): Introduction to statistical analysis and inference. John Wiley & Sons Inc., New York.

Arnold, G.E. (1948): Die traumatischen und konstitutionellen Störungen der Stimme und Sprache. Urban und Schwarzenberg, Wien.

Arnold, G.E. (1955a): Vocal rehabilitation of paralytic dysphonia. 1. Cartilage injection into a paralyzed vocal cord. Arch Otolaryngol 62, 1-17.

Arnold, G.E. (1955b): Vocal rehabilitation of paralytic dysphonia. 2. Acoustic analysis of vocal function. Arch Otolaryngol 62, 593-601.

Arnold, G.E. (1958): Vocal rehabilitation of paralytic dysphonia. 4. Paralytic dysphonia due to unilateral recurrent nerve paralysis. Arch Otolaryngol 68, 284-300.

Arnold, G.E. (1959): Vocal rehabilitation of paralytic dysphonia. 5. Vocal symptomatology after bilateral loss of abduction. Arch Otolaryngol 70, 444-453.

Bartels, H., Bücherl, E., Hertz, C.W., Rodewald, G. and Schwab, M. (1959): Methoden und Beispiele klinischer Anwendung. In: Lungenfunktionsprüfungen. Springer Verlag Berlin, 146-161.

Bastian, H.J., Sasama, R. and Unger, E. (1978): Aerodynamische Leistungsprüfung und Funktionsdiagnostik der normalen Frauenstimme. Folia Phoniatr 30, 85-93.

Berendes, J. (1938): Zur Entstehung und Behandlung der Dysphonia Spastica. Z Hals-, Nasen-, u Ohrenheilkd 44, 78.

Berendes, J. (1956): Neuere Ergebnisse über Bewegungsstörungen des Kehlkopfes. Arch f Ohren-, Nasen-, u Kehlkopfheilkd 169, 1-172.

Berg, Jw. van den (1953): Physica van de stemvorming, met toepassingen. Thesis Groningen.

Berg, Jw. van den (1954): Ueber die Koppelung bei der Stimmbildung. I. Ansatzrohr-Kehlkopf und II. Stimmlippe-Stimmlippe. Z Phon u Allg Sprachw 8, 281-292.

Berg, Jw. van den (1956): Direct and indirect determination of the mean subglottic pressure. Folia Phoniatr 8, 1-24.

Berg, Jw. van den, Zantema, J.T. and Doornenbal, P. (1957): On the air resistance and the Bernoulli effect of the human larynx. J Acoust Soc Am 29, 626-631.

Berg, Jw. van den (1958): Myoelastic-aerodynamic theory of voice production. J Speech Hear Res 1, 227-244.

Berg, Jw. van den and Tan, T.S. (1959): Results of experiments with human larynxes. Pract Otorhinolaryngol 21, 425-450.

Berg, Jw. van den and Vennard, W. (1959): Toward an objective vocabulary for voice pedagogy. NATS Bulletin 15, 10-15.

Berg, Jw. van den (1961): Physiological basis of language. LOGOS 4, 56-66.

Berg, Jw. van den (1968): Mechanism of the larynx and the laryngeal vibrations. In: Manuel of phonetics. Ed. B. Malmberg, North-Holland Publ Comp, Amsterdam, 278-308.

Bevington, Ph. R. (1969): Data reduction and error analysis for the physical sciences. McGraw-Hill Book Comp, New York.

Biesalski, P. (1973): Phoniatrie und Paedoaudiologie. Georg Thieme Verlag, Stuttgart.

Blumenfeld, W., Turney, S. and Cowley, R.A. (1973): Mathematical model for flow in the heated Fleisch pneumotachometer. Med Biol Eng 11, 546-551.

Blumenfeld, W., Wilson, P.O. and Turney, S. (1974): A mathematical model for the ultrasonic measurement of respiratory flow. Med Biol Eng 12, 621-625.

Böhme, G. (1972): Untersuchungsmethoden der Stimme und Sprache. J.A. Barth, Leipzig.

Böhme, G. (1974): Stimm-, Sprech- und Sprachstörungen. Gustav Fischer Verlag, Stuttgart.

Boone, D.R. (1977): The voice and voice therapy. Prentice-Hall Inc, 2nd ed, Englewood Cliffs, New Jersey.

Bottaccini, M.R., Burton, D.L. and Lim, Th.P.K. (1967): Calibration of high-frequency manometers with the shock-tube. J Appl Physiol 22, 832-835.

Bouhuys, A., Proctor, D.F. and Mead, J. (1966): Kinetic aspects of singing. J Appl Physiol 21, 483-495.

Bouhuys, A. (1966): Analyse van de stemgeving met behulp van druk-volume-diagrammen. Ned Tijdschr Geneeskd 110, 945-947.
Bouhuys, A. Mead, J., Proctor, D.F. and Stevens, K.N. (1968): Pressure-flow events during singing. Ann NY Acad Sci 155, 165-176.
Brodnitz, F.S. (1976): Spastic dysphonia. Ann Otol Rhinol Laryngol 85, 210-214.
Bunch, M.A. (1976): A cephalometric study of structures of the head and neck during sustained phonation of covered and open qualities. Folia Phoniatr 28, 321-328.
Buytendijk, H.J. (1949): Oesophagusdruk en longelasticiteit. Thesis Groningen.

Cagniard-Latour, (1837): C R Acad Sci, 394. Cited by Roudet (1900a).
Calvet, J. and Malhiac, (1952): Courbes vocales et mue de la voix. J Fr Otorhinolaryngol 1, 115-124.
Calvet, J. (1953): Etudes phonométriques. In: La voix, Cours Internationale de Phonologie et Phoniatrie. Libraire Maloine, Paris, 67-78.
Cavagna, G.A. and Margaria, R. (1965): An analysis of the mechanics of phonation. J Appl Physiol 20, 301-307.
Cavagna, G.A. and Margaria, R. (1968): Airflow rates and efficiency changes during phonation. Ann NY Acad Sci 155, 152-164.
Cavagna, G.A. and Camporesi, E.M. (1974): Glottic aerodynamics and phonation. In: Ventilatory and phonatory control systems. Ed. B. Wyke, London, 76-92.
Cleveland, Th.F. (1977): Acoustic properties of voice timbre types and their influence on voice classification. J Acoust Soc Am 61, 1622-1629.
Coblenzer, H. and Muhar, F. (1976): Atem und Stimme. Oesterreichischer Bundes Verlag für Unterricht, Wissenschaft und Kunst, Wien.
Colton, R.H. (1972): Spectral characteristics of the modal and falsetto registers. Folia Phoniatr 24, 337-344.
Colton, R.H. (1973a): Vocal intensity in the modal and falsetto registers. Folia Phoniatr 25, 62-70.
Colton, R.H. (1973b): Some acoustic parameters related to the perception of modal-falsetto voice quality. Folia Phoniatr 25, 302-311.

Colton, R.H. and Hollien, H. (1973a): Perceptual differentiation of the modal and falsetto registers. Folia Phoniatr 25, 270-280.
Colton, R.H. and Hollien, H. (1973b): Physiology of vocal registers on singers and non-singers. In: Vocal registers in singing. Ed. J.W. Large, Mouton, The Haque.
Cooper, M. (1973): Modern techniques of vocal rehabilitation. Charles C. Thomas Publishers, Springfield Illinois.
Cooper, M. and Cooper, M.H. (1977): Approaches to vocal rehabilitation. Charles C. Thomas Publishers, Springfield Illinois.

Dalhoff, K. and Kitzing, P. (1977a): Bemerkungen zur Akzentmethode nach Smith für die Behandlung von Stimm- und Sprechstörungen. Teil I. HNO 25, 102-105.
Dalhoff, K. and Kitzing, P. (1977b): Bemerkungen zur Akzentmethode nach Smith für die Behandlung von Stimm- und Sprechstörungen. Teil II. HNO 25, 214-217.
Damsté, P.H. (1973a): De pathologische stembandfunctie. Stafleu, Leiden.
Damsté, P.H. (1973b): Vocal disorders: a guide to their diagnosis. ORL 35, 149-153.
Damsté, P.H. and Lerman, J.W. (1975): An introduction to voice pathology, functional and organic. Charles C. Thomas Publishers, Springfield Illinois.
Damsté, P.H. (1978): Stembandkramp. Ned Tijdschr Geneeskd 122, 1313-1315.
Deinse, J.B. van (1973): Some remarks about the covering of the singing voice. ORL 35, 154-157.
Deinse, J.B. van, Frateur, L. and Keizer, J. (1974): Problems of the singing voice. Folia Phoniatr 26, 428-434.
Deinse, J.B. van and Goslings, W.R.O. (1978): De zangtechniek in Nederland. Staatsuitgeverij, 's Gravenhage/Rijswijk.
Diem, K. and Lentner, C. (1968): Documenta Geigy, Wissenschaftliche Tabellen. Geigy, Basel, 7e Auflage.
Döhne, E. (1944): Die organisch bedingte einseitige Leitungsunterbrechung des Nervus laryngeus inferior und ihre Stimmveränderungen. Arch f Ohren-, Nasen-, u Kehlkopfheilkd 154, 96-140.
Donleben, P.G. (1959): Studies on lung mechanics. Thesis Groningen.

Draper, M.H., Ladefoged, P. and Whitteridge, D. (1959): Respiratory muscles in speech. J Speech Hear Res 2, 16-27.

Draper, M.H. and Ladefoged, P. (1960): Expiratory pressures and air flow during speech. Brit Med J 18, 1837-1843.

Egan, D.F. (1969): Fundamentals of inhalation therapy. The C.V. Mosby Comp, Saint Louis.

Farnsworth, D.W. (1940): High-speed motion pictures of the human vocal cords. Bell Lab Rec, 203-208.

Fenn, W.H. and Rahn, H. (1964): Handbook of Physiology, section 3: Respiration. Am Physiological Soc, Washington D.C..

Ferris, B.G., Opie, L. and Mead, J. (1960): Partitioning of respiratory resistance in man. Fed Proc 19, 377.

Ferris, B.G., Mead, J. and Opie, L. (1964): Partitioning of respiratory flow resistance in man. J Appl Physiol 19, 653-65B.

Fischer, A.B., Dubois, A.B. and Hyde, R.W. (196B): Evaluation of the forced oscillation technique for the determination of resistance to breathing. J Clin Invest 47, 2045-2057.

Fleisch, A. (1925): Der Pneumotachograph; ein Apparat zur Geschwindigkeitsregistrierung der Atemluft. Pflügers Arch 209, 713.

Fleisch, A. (1956): Le pneumotachographe. Acta Helv Physiol 14, 363-36B.

Fletcher, G. (1969): Respiratory mechanics. In: Techniques in clinical physiology. Ed. J. Weldon Bellville, Collier-McMillan Ltd, London.

Fry, D.L., Stead, W.W., Ebert, R.V., Lubin, R.I. and Swells, H. (1952): The measurement of intraesophageal pressure and its relationship to intrathoracic pressure. J Lab Clin Med 40, 664-673.

Glatz, H. (1970): Subglottische Druckmessungen bei Patienten mit funktionellen und organischen Stimmstörungen. Dissertation München.

Gordon, M.T. (197B): Physical measurements in a clinically orientated voice pathology clinic. Proc XVIIth Int Congr Log and Phon Copenhagen, 401-41B.

Gordon, M.T., Morton, F.M. and Simpson, I.C. (197B): Air flow measurements in diagnosis assessment and treatment of mechanical dysphonia. Folia Phoniatr 30, 161-174.

Gould, W.J. (1971): Effect of respiratory and postural mechanisms upon action of the vocal cords. Folia Phoniatr 23, 211-224.

Greene, M.C.L. (1972): The voice and its disorders. Pitman Medical, London, 3rd ed.

Greer, J.R. (1964): Greer micromanometer. World Med Electr and Instrum 3.

Greer, J.R. (1966): Integrated pneumotachograph tracings and lung volumes. World Med Electr and Instrum 4, 116-118.

Grenvik, Å., Hedstrand, U. and Sjögren, H. (1966): Problems in pneumotachography. Acta Anaesthesiol Scan 10, 147-155.

Grenvik, Å. and Hedstrand, U. (1966): The reliability of pneumotachography in respirator ventilation. Acta Anaesthesiol Scan 10, 157-167.

Gundermann, H. (1970): Die Berufsdyphonie. Georg Thieme Verlag, Leipzig.

Gutzmann, H. and Loewy, A. (1920): Ueber den intrapulmonalen Druck und den Luftverbrauch bei der normalen Atmung, bei phonetischen Vorgängen und bei der exspiratorischen Dyspnoe. Pflügers Arch 180, 111-137.

Hardcastle, W.J. (1976): Physiology of speech production. Academic Press, London.

Herzog, P. (1970): A precision method for the dynamic volume-flow calibration during pneumotachography. In: Patient monitoring. Ed. J.F. Crul and J.P. Payne, Exerpta Medica, Amsterdam, 62-68.

Hilvering, Chr. (1963): Longmechanische onderzoekingen bij patienten met longtuberculose. Thesis Groningen.

Hippel, K. and Mrowinski, D. (1978): Untersuchung stimmgesunder und stimmkranker Personen nach der Methode der Pneumotachographie. HNO 26, 421-423.

Hirano, M., Koike, Y. and Leden, H. von (1968): Maximum phonation time and air usage during phonation (clinical study). Folia Phoniatr 20, 185-201.

Hirano, M., Koike, Y. and Joyner, J. (1969): Style of phonation. An EMG investigation of some laryngeal muscles. Arch Otolaryngol 89, 902-907.

Hirano, M., Ohala, J. and Vennard, W. (1969): The function of laryngeal muscles in regulating fundamental frequency and intensity of phonation. J Speech Hear Res 12, 616-628.

Hirano, M., Vennard, W. and Ohala, J. (1970): Regulation of register, pitch and intensity of voice. An electromyographic investigation of intrinsic laryngeal muscles. Folia Phoniatr 22, 1-20.
Hirano, M. (1974): Regulatory mechanism of voice in singing. (Instructional film). Dept of Otolaryngology, Kurume Univ, Japan. Folia Phoniatr 26, 192.
Hirano, M. (1975): Phonosurgery, basic and clinical investigations. (partly in Japanese, translated with the help of M. Yanagida and Tj. de Graaf). Otologica (Fukuoka) 21, suppl 1.
Hirschfelder, J.O., Curtiss, C.F. and Bird, R.B. (1954): The molecular theory of gases and liquids. Cited in: Handbook of Physiology. Ed. W.H. Fenn and H. Rahn. Section 3: Respiration, vol. I, 143.
Höfner, G. and Siegert, C. (1975): Beitrag zur objektiven-komplexen Leistungsdiagnostik des Stimmorgans. Wiss Zeitschr Friedrich-Schiller Univ Jena 24, 137-147.
Hollien, H. (1972): Three major vocal registers: a proposal. Proc VIIth Int Congr Phon Sci Montreal 1971. Mouton, The Haque.
Hollien, H. (1974): On vocal registers. J Phonetics 2, 125-143.
House, A.S. (1959): A note on optimal vocal frequency. J Speech Hear Res 2, 55-60.
Husler, F. and Rodd-Marling, Y. (1978): Singen, die physische Natur des Stimmorganes. Schott Mainz Ed 6752, le Druck 1965/2e Auflage.
Hyatt, R.E. and Wilcox, R.E. (1960): Partition of pulmonary flow resistance into upper and lower airway components. Fed Proc 19, 376.

Isshiki, N. (1959): Regulatory mechanism of the pitch and volume of voice. Oto-rhino-laryngological Clinic Kyoto 52, 1065-1094.
Isshiki, N. (1961): Voice and subglottic pressure. Stud Phonologica 1, 86-94.
Isshiki, N. (1964): Regulatory mechanism of voice intensity variation. J Speech Hear Res 7, 17-29.
Isshiki, N. and Leden, H. von (1964): Hoarseness: Aerodynamic studies. Arch Otolaryngol 80, 206-213.
Isshiki, N. (1965): Vocal intensity and air flow rate. Folia Phoniatr 17, 92-104.

Isshiki, N., Yanagihara, N. and Morimoto, M. (1966): Approach to the objective diagnosis of hoarseness. Folia Phoniatr 18, 393-400.

Isshiki, N., Okamura, H. and Morimoto, M. (1967): Maximum phonation time and air flow rate during phonation: simple clinical tests for vocal function. Ann Otol Rhinol Laryngol 76, 998-1007.

Isshiki, N., Okamura, H., Tanabe, M. and Morimoto, M. (1969): Differential diagnosis of hoarseness. Folia Phoniatr 21, 9-19.

Iwata, S. and Leden, H. von (1970a): Clinical evaluation of Vocal Velocity Index in laryngeal disease. Ann Otol Rhinol Laryngol 79, 259-269.

Iwata, S. and Leden, H. von (1970b): Phonation Quotient in patients with laryngeal diseases. Folia Phoniatr 22, 117-128.

Iwata, S., Leden, H. von and Williams, D. (1972): Air flow measurement during phonation. J Com Dis 5, 67-79.

Jeschek, J. (1953): Theorie und Klinik der Stimmbandlähmung. Arch Klin Exp Ohren Nasen Kehlkopfheilkd 162, 237-303.

Jeschek, J. (1958): Ueber den derzeitigen Stand der Forschung auf dem Gebiet der Stimmbandlähmungen. Folia Phoniatr 10, 129-149.

Jeschek, J. (1961): Ueber die Eigendämpfung der Stimmbänder beim Schwingungsvorgang. Acta Otolaryngol 53, 249-258.

Kelman, A.W., Gordon, M.T., Simpson, I.C. and Morton, F.M. (1975): Assessment of vocal function by air-flow measurements. Folia Phoniatr 27, 250-263.

Kestin, J. (1963): Viscosity of gases. In: American Institute of physics handbook. Ed. E.D. Gray, McGraw-Hill Book Comp, New York, 359-365.

Kittel, G. and Moser, M. (1976): Ganzkörperplethysmographische Untersuchungen bei Stotterern: subglottische Druckmessungen. Proc XVIth Int Congr Log and Phon Interlaken 1974, Karger Basel, 251-256.

Kitzing, P. and Löfqvist, A. (1975): Subglottal and oral air pressures during phonation - preliminary investigation using a miniature transducersystem. Med Biol Eng 13, 644-648.

Kleinsasser, O. (1968): Mikrolaryngoskopie und endolaryngeale Mikrochirurgie. Technik und typische Befunde. Schattauer Stuttgart/ New York.

Klingholz, F. and Siegert, C. (1972): Beziehungen zwischen Stimm-Schalldruck und intrathorakalem Druck beim Stimmeinsatz. Folia Phoniatr 24, 381-386.

Koike, Y., Hirano, M. and Leden, H. von (1967): Vocal initiation: acoustic and aerodynamic investigations of normal subjects. Folia Phoniatr 19, 173-182.

Koike, Y. and Hirano, M. (1968): Significance of Vocal Velocity Index. Folia Phoniatr 20, 285-296.

Koike, Y. and Hirano, M. (1973): Glottal-area time function and subglottal-pressure variation. J Acoust Soc Am 54, 1618-1627.

Kunze, L.H. (1962): An investigation of the changes in subglottal air pressure and rate of air flow accompanying changes in fundamental frequency, intensity, vowels and voice registers in adult male speakers. Thesis Iowa.

Kunze, L.H. (1964): Evaluation of methods of estimating subglottal air pressure. J Speech Hear Res 7, 151-164.

Ladefoged, P., Draper, M.H. and Whitteridge, D. (1958): Syllables and stress. Miscellanea Phonetica 111, 1-14.

Ladefoged, P. (1960): The regulation of subglottal pressure. Folia Phoniatr 12, 169-175.

Ladefoged, P. (1962): Subglottal activity during speech. Proc IVth Congr Int Phon Sci Helsinki, 73-91.

Ladefoged, P. (1963): Some physiological parameters in speech. Lang Speech 6, 109-119.

Ladefoged, P. and McKinney, N.P. (1963): Loudness, sound pressure and subglottal pressure in speech. J Acoust Soc Am 35, 454-460.

Ladefoged, P. (1964): Comment on "evaluation of methods of estimating subglottal air pressure". J Speech Hear Res 7, 291-292.

Lange, (1967): Handbook of chemistry. 10th ed. McGraw-Hill Book Comp, New York.

Langnickel, R. and Koburg, E. (1970): Die endolaryngeale lateral-fixation des Stimmbandes zur operativen Behandlung der beider-seitigen Posticusparese. HNO 18, 239-242.

Langnickel, R. and Koburg, E. (1972a): Zur Technik der endolaryngealen Lateralfixation. Z Laryngol Rhinol Otol 51, 249-252.

Langnickel, R. and Koburg, E. (1972b): Ergebnisse der endolaryngealen Lateralfixation nach beiderseitiger Stimmbandlähmung. Z Laryngol Rhinol Otol 52, 330-335.

Langnickel, R. (1976): An endolaryngeal method of vertico-lateral transposition of the vocal cord for bilateral abductor paralysis. Laryngoscope 86, 1020-1028.

Large, J.W. (1968): An acoustical study of isoparametric tones in the female chest and middle registers in singing. NATS Bulletin dec., 12-15.

Large, J.W. (1969): A method for the selection of samples for acoustical and perceptual studies of voice registers. NATS Bulletin febr., 40-42.

Large, J.W. and Shipp, T. (1969): The effect of certain parameters on the perception of vocal registers. NATS Bulletin okt., 12-15.

Large, J.W., Iwata, S. and Leden, H. von (1970): The primary female register transition in singing: aerodynamic study. Folia Phoniatr 22, 385-396.

Large, J.W. and Iwata, S. (1971): Aerodynamic study of vibrato and voluntary 'straight tone' pairs in singing. Folia Phoniatr 23, 50-65.

Large, J.W., Iwata, S. and Leden, H. von (1972): The male operatic head register versus falsetto. Folia Phoniatr 24, 19-29.

Large, J.W. (1973a): Acoustic study of register equalization in singing. Folia Phoniatr 25, 39-61.

Large, J.W. (1973b): Vocal registers in singing. Mouton, The Haque.

Leanderson, R. and Grape, B. (1967): Voice aerodynamics after chordectomy. Acta Otolaryngol (Suppl) 224, 495-500.

Leden, H. von (1968): Objective measures of laryngeal function and phonation. Ann NY Acad Sci 155, 56-67.

Leeper, H.A. (1976): Voice initiation characteristics of normal children and children with vocal nodules: a preliminary investigation. J Com Dis 9, 83-94.

Lieberman, P. (1968): Direct comparison of subglottal and esophageal pressure during speech. J Acoust Soc Am 43, 1157-1164.

Lilly, J.C. (1950): Flow meter for recording respiratory flow of human subjects. In: Methods in medical research, vol. II. Ed. J.H. Comroe, Yearbook Publ Inc, Chicago, 113-121.

Loebell, E. (1969): Ueber die direkte Messung des subglottischen Luftdruckes. Arch Klin Exp Ohren Nasen Kehlkopfheilkd 194, 316-320.

Luchsinger, R. (1951): Schalldruck- und Geschwindigkeitsregistrierung des Atemluft beim Singen. Folia Phoniatr 3, 25-51.

Luchsinger, R. (1953): Physiologie der Stimme. Folia Phoniatr 5, 58-127.

Luchsinger, R. and Arnold G.E. (1965): Voice, speech and language. Clinical communicology, its physiology and pathology. Wadsworth Publ Comp, Belmont California.

Luchsinger, R. and Arnold, G.E. (1970): Handbuch der Stimm- und Sprachheilkunde. Teil I: Die Stimme und ihre Störungen. Springer Verlag, Wien.

Margaria, R. and Cavagna, G. (1959): Il meccanismo della fonazione. Boll Soc Ital Biol Sper 35, 2075-2077.

Marshall, R. and Dubois, A.B. (1956): The measurement of viscous resistance of the lung tissue in normal man. Clin Sci 15, 161-170.

Marshall, R. (1964): Objective tests of respiratory mechanics. In: Handbook of physiology. Ed. W.H. Fenn and H. Rahn. Section 3: Respiration, vol. II, 1399-1411.

McCall, C.B., Hyatt, R.E., Noble, F.W. and Fry, A.L. (1957): Harmonic content of certain respiratory flow phenomena of normal individuals. J Appl Physiol 10, 215-218.

McDonald, D.A. (1960): Blood flow in arteries. Edward Arnold Publ Ltd, London.

McGlone, R.E. (1963): An experimental study of a technique of intra-esophageal pressure measurement as a method for estimating subglottic pressure. Thesis State University of Iowa.

McGlone, R.E. (1967): Air flow during vocal fry phonation. J Speech Hear Res 10, 299-304.

McGlone, R.E. (1970): Air flow in the upper register. Folia Phoniatr 22, 231-238.

McGlone, R.E. and Shipp, T. (1971): Some physiologic correlation of vocal fry phonation. J Speech Hear Res 14, 769-775.

McIlroy, M.B., Mead, J., Selverstone, N.J. and Radford, E.P. (1955): Measurement of lung tissue viscous resistance using gases of equal kinematic viscosity. J Appl Physiol 7, 485-490.

Mead, J. and Whittenberger, J.L. (1953): Physical properties of human lungs measured during spontaneous respiration. J Appl Physiol 5, 779-796.

Mead, J., McIlroy, M.B., Selverstone, N.J. and Kristel, B.C. (1955): Measurement of intraesophageal pressure. J Appl Physiol 7, 491-495.

Mead, J., Bouhuys, A. and Proctor, D.F. (1968): Mechanisms generating subglottic pressure. Ann NY Acad Sci 155, 177-181.

Mendl, J. (1970): Direkt und quantitative subglottische Druckmessungen während der Atmung und Stimmgebung bei Gesunden. Dissertation München.

Milic-Emili, J., Mead, J., Turner, J.M. and Glauser, E.M. (1964): Improved technique for estimating pleural pressure from esophageal balloons. J Appl Physiol 19, 207-211.

Miller, R. (1977): English, French, German and Italian techniques of singing: A study in national tonal preferences and how they relate to functional efficiency. The Scarecrow Press Inc, Metuchen N.J..

Minifie, F.D., Hixon, Th.J. and Williams, F. (1973): Normal aspects of speech, hearing and language. Prentice-Hall Inc, Englewood Cliffs, New Jersey.

Moser, M. and Kittel, G. (1979): Automatisierte bodyplethysmographische Atemmessungen: Der phonatorische Wirkungsgrad. HNO 27, 100-102.

Murry, Th. (1971): Subglottal pressure and airflow measures during vocal fry phonation. J Speech Hear Res 14, 544-551.

Murry, Th. and Brown, W.S. jr. (1971): Subglottal air pressure during two types of vocal activity: vocal fry and modal phonation. Folia Phoniatr 23, 440-449.

Murry, Th. and Schmitke, L.K. (1975): Air flow onset and variability. Folia Phoniatr 27, 401-409.

Murry, Th., Singh, S. and Sargent, M. (1977): Multidimensional classification of abnormal voice qualities. J Acoust Soc Am 61, 1630-1635.

Nishida, Y. and Suwoya, H. (1964): Indirect measuring method of subglottic pressure in the voice production. Intraesophageal method and interruption method. Otologica (Fukuoka) 10, 264-270.
Nold, H. (1967): Subglottische Druckmessungen bei Patienten mit malignen Larynxtumoren während der Phonation. Dissertation München.

Osborn, J.J., Beaumont, J.O., Raison, J.G.A., Rusell, J. and Gerbode, F. (1968): Measurement and monitoring of acutely ill patients by digital computer. Surgery 64, 1057-1070.
Osborn, J.J., Elliott, S.E., Segger, J. and Gerbode, F. (1969): Continuous measurement of lung mechanics and gas exchange in the critically Ill. Med Res Eng 5, 19-24.
Otis, A.B. (1965): Quantitative relationships in steady-state gas exchange. In: Handbook of physiology. Ed. W.H. Fenn and H. Rahn. Section 3: Respiration, vol. II, Chapter 27. Am Physiol Soc, Washington D.C., 681-698.

Pahn, J. (1964): Der therapeutische Wert nasalierter Vokalklänge in der Behandlung funktioneller Stimmerkrankungen. Folia Phoniatr 16, 249-263.
Pahn, J. (1966): Zur Entwicklung und Behandlung funktioneller Singstimmerkrankungen. Folia Phoniatr 18, 117-130.
Pascher, W. (1975): Angewandte Phoniatrie. I. Methodik der Stimmuntersuchung. HNO 23, 84-90.
Perkins, W.H. and Yanagihara, N. (1968): Parameters of voice production. I. Some mechanisms for the regulation of pitch. J Speech Hear Res 11, 246-267.
Perkins, W.H. and Koike, Y. (1969): Patterns of subglottal pressure variations during phonation. Folia Phoniatr 21, 1-8.
Proctor, D.F. (1968): The physiologic basis of voice training. Ann NY Acad Sci 155, 208-228.
Proctor, D.F. (1974): Breathing mechanics during phonation and singing. In: Ventilatory and phonatory control systems. Ed. B. Wyke, London, 39-57.
Ptacek, P.H. and Sander, E.K. (1963a): Maximum duration of phonation. J Speech Hear Disord 28, 171-182.

Ptacek, P.H. and Sander, E.K. (1963b): Breathiness and phonation length. J Speech Hear Disord 28, 267-272.

Roudet, L. (1900a): De la dépense d'air dans la parole et de ses conséquences phonetiques. La Parole, 201-230.
Roudet, L. (1900b): Recherches sur le rôle de la pression sous-glottique dans la parole. La Parole, 599-612.
Rubin, H.J., LeCover, M. and Vennard, W. (1967): Vocal intensity, subglottic pressure and air flow relationship in singers. Folia Phoniatr 19, 393-413.

Sawashima, M., Yoshioka, Honda, K., Ushijima, T., and Hirose, H. (1978): Clinical evaluation of air usage during phonation. Proc XVIIth Int Congr Log and Phon Copenhagen, 419-422; 451-454.
Schilling, R. (1922): Untersuchungen über das Stauprinzip. Zeitschr HNO-Heilkd 1, 314-347.
Schilling, R. (1925): Untersuchungen über die Atembewegungen beim sprechen und singen. 1/2/3/4. Monatschr Ohrenheilkd Laryngorhinol 59, 51-81; 134-153; 313-343; 454-467; 634-668.
Schiratzki, H. (1964): Upper airway resistance in normal man during mouth breathing. Acta Otolaryngol 58, 535-554.
Schiratzki, H. (1965a): Upper airway resistance during mouth breathing in patients with unilateral and bilateral paralysis of the recurrent laryngeal nerve. Acta Otolaryngol 59, 475-496.
Schiratzki, H. (1965b). The oral and laryngeal components of the upper airway resistance during mouth breathing. Acta Otolaryngol 60, 71-82.
Schönhärl, E. (1960): Die Stroboskopie in der praktischen Laryngologie. Georg Thieme Verlag, Stuttgart.
Schuck, M. (1971): Direkte quantitative Messungen des subglottischen Luftdruckes bei Patienten mit chronischer Heiserkeit. Dissertation München.
Schutte, H.K. (1975): Over het fonetogram. Tijdschr Log Fon 47, 82-92.
Schutte, H.K. and Berg, Jw. van den (1976): Determination of the subglottic pressure and the efficiency of sound production in patients with disturbed voice production. Proc XVIth Int Congr Log and Phon Interlaken 1974, 415-420.

Schwabe, F. and Siegert, C. (1973): Bemerkungen zum Beitrag "vocal intensity, subglottic pressure, and air flow relationships in singers". Folia Phoniatr 25, 150-154.

Sedláčková, E. (1960): Les dysphonies hypercinétiques des enfants, causées par surmenage vocal. Folia Phoniatr 12, 48-60.

Seidner, W., Wendler, J. and Stürzebecher, E, (1975): Das normale Phono-Pneumotachogramm. Proc XVIth Int Congr Log and Phon Interlaken, 421-426.

Seidner, W. and Stürzebecher, E. (1978): Variabilität normaler Phono-Pneumotachogramme. Proc XVIIth Int Congr Log and Phon Copenhagen, 563-569.

Seidner, W. and Wendler, J. (1978): Die Sängerstimme. Henschelverlag Berlin.

Seymour, J. (1972a): Acoustic analyses of singing voices: I. Sound samples and room responses. Acustica 27, 203-208.

Seymour, J. (1972b): Acoustic analyses of singing voices: II. Frequency and amplitude vibrato analyses. Acustica 27, 209-217.

Seymour, J. (1972c): Acoustic analyses of singing voices: III. Spectral components formants and the glottal source. Acustica 27, 218-227.

Shipp, T. and McGlone R.E. (1971): Laryngeal dynamics associated with voice frequency change. J Speech Hear Res 14, 761-768.

Siegert, C. (1969): Der intrathorakale Druck und seine Beziehungen zur Stimmfunktion. Folia Phoniatr 21, 98-104.

Siegert, C. (1971): Methodik zur Bestimmbarkeit der Phonationsschwelle und ihr diagnostischer Wert. Das Deutsche Gesundheitswesen 26, 1083-1085.

Siegert, C. and Klingholz, F. (1973): Testing system for voice function. Proc Xth Int Congr Med Biol Eng, 141.

Silverman, L. and Whittenberger, J.L. (1950): Clinical pneumotachograph. In: Methods in medical research. Ed. J.H. Comroe. Vol. II. Yearbook Publ Inc Chicago, 104-112.

Snedecor, G.W. and Cochran, W.G. (1968): Statistical methods. Iowa State University Press. 6th ed.

Sokal, R.R. and Rohlf, F.J. (1969): Biometry, the principles and practice of statistics in biological research. W.H. Freedman and Comp, San Francisco.

Spells, K.E. (1969): Comparative studies in lung mechanics based on a survey of literature data. Resp Physiol 8, 37-57.

Stead, W.W., Fry, D.L. and Ebert, R.V. (1952): The elastic properties of the lung in normal men and in patients with chronic pulmonary emphysema. J Lab Clin Med 40, 674-681.

Stern, H. (1929): Die phoniatrische 8ehandlung der Rekurrenslähmung. In: Handbuch der Hals- usw. Heilkd. Ed. A. Denker and O. Kahler, Springer Verlag, Berlin, vol. 5, 930-942.

Strenger, F. (1958): Mesure de la pression d'air sous-glottique, de la pression acoustique et de la durée de la prononciation des differents sons du langage suédois au cours de la phonation. J Fr Otorhino-laryngol 7, 101-113.

Strenger, F. (1959): Methods for direct and indirect measurements of the subglottic air-pressure in phonation. Stud Linguistica 13, 98-112.

Stürzebecher, E., Seidner, W., Wagner, H. and Wendler, J. (1973): Erfassung von Atemgrössen während der Phonation. Monatschr Ohrenheilkd Laryngorhinol 107, 271-278.

Sundberg, J. (1970): Formant structures and articulation of spoken and sung vowels. Folia Phoniatr 22, 2B-48.

Sundberg. J. (1973): The source spectrum in professional singing. Folia Phoniatr 25, 71-90.

Sundberg, J. (1975): Formant technique in a professional female singer. Acustica 32, 89-96.

Sundberg, J. (1977): The acoustics of the singing voice. Sci Am, 82-91.

Tan, T.S. (1960): Proeven over geluidsproduktie in de menselijke larynx. Thesis Groningen.

Tostmann, R., Siegert, C. and Klingholz, F. (1979): Ballon oder Miniaturdruckwandler bei der Messung Druckverläufe zur Stimm-funktionsprüfung. Med Tech 19, 22-26.

Turney, S.Z. and Blumenfeld, W. (1973): Heated Fleisch pneumotachometer: a calibration procedure. J Appl Physiol 34, 117-121.

Vaughn, A.O. (1965): An experimental study of oral and nasal air flow during sustained vowel production. Thesis University of Oklahoma.

Veldkamp, K. (1973): De techniek van het spreken. Revised by A.G. Zijderveld-Menalda. Wolters-Noordhoff, Groningen,

Vennard, W. and Isshiki, N. (1964): Coup de glotte, a misunderstood expression. NATS Bulletin 20, 15-18.

Vennard, W. (1967): Singing, the mechanism and the technique. Fischer Inc, New York.

Vennard, W., Hirano, M. and Ohala, J. (1970a): Part I. Laryngeal synergy in singing. NATS Bulletin 27, 16-21.

Vennard, W., Hirano, M. and Ohala, J. (1970b): Part II. Chest, head and falsetto. NATS Bulletin 27, 30-37.

Vennard, W. and Hirano, M. (1971a): Part III. Varieties of voice production. NATS Bulletin 27, 26-32.

Vennard, W., Hirano, M. and Fritzell, B. (1971b): Part IV. The extrinsic laryngeal muscles. NATS Bulletin 27, 22-30.

Vierhout, R.R. (1963): The response of catheter manometer systems used for direct blood pressure measurement. Thesis Nijmegen.

Vogelsänger, G.Th. (1954): Experimentelle Prüfung der Stimmleistung beim Singen. Folia Phoniatr 6, 193-227.

Waar, C.H. and Damsté, P.H. (1968): Het fonetogram. Tijdschr Log Fon 40, 198-201.

Weast, R.C. (1968): Handbook of chemistry and physics. The Chemical Rubber Co, Cleveland Ohio, 49th ed.

Weiss, D. (1932a): Ein Resonanzphänomen der Singstimme. Monatschr Ohrenheilkd Laryngorhinol 66, 964-967.

Weiss, D. (1932b): Zur Frage der Registerbruchstellen. Die Wirkung vorgeschalteter Resonanzröhren auf die Stimme. Z HNO 22, 353-358.

Wendler, J., Seidner, W., Rose, A., Simon, B. and Ulbrich, H. (1973): Zur praktischen Nomenklatur der funktionellen Dysphonien. Folia Phoniatr 25, 30-38.

Wendler, J. and Seidner, W. (1977): Lehrbuch der Phoniatrie. VEB Georg Thieme, Leipzig.

Werner-Kukuk, E. and Leden, H. von (1970): Vocal initiation. High speed cinematographic studies on normal subjects. Folia Phoniatr 22, 107-116.

Wesseling, K.H. and Vollenhoven, E. van (1969): Catheter-manometer systems. TNO-nieuws 24, 603-616.

Wilson, D.K. (1979): Voice problems of children. Williams and Wilkins Comp, Baltimore, 1st ed. 1972.

Winckel, F. (1952): Elektroakustische Untersuchungen an der menschlichen Stimme. Folia Phoniatr 4, 93-113.

Winckel, F. (1953): Physikalische Kriterien für die objektive Stimmbeurteilung. Folia Phoniatr 5, 232-252.

Wyke, B.D. (1974a): Respiratory activity of intrinsic laryngeal muscles: An experimental study. In: Ventilatory and phonatory control systems. Ed. B.D. Wyke, London.

Wyke, B.D. (1974b): Laryngeal myotatic reflexes and phonation. Folia Phoniatr 26, 249-264.

Wyke, B.D. (1974c): Laryngeal neuromuscular control systems in singing: A review of current concepts. Folia Phoniatr 26, 295-306.

Wyke, B.D. (1974d): Phonatory reflex mechanisms and stammering. Folia Phoniatr 26, 321-338.

Wyke, B.D. (1976): Laryngeal reflex mechanisms in phonation. Folia Phoniatr 28, 52B-537.

Wyvekate, M.L. (1972): Verklarende statistiek. Spectrum, Utrecht.

Yanagihara, N. and Leden, H. von (1966): The cricothyroid muscle during phonation. Ann Otol Rhinol Laryngol 75, 987-1007.

Yanagihara, N., Koike, Y. and Leden, H. von (1966): Phonation and respiration (function study in normal subjects). Folia Phoniatr 18, 323-340.

Yanagihara, N. (1967a): Significance of harmonic changes and noise components in hoarseness. J Speech Hear Res 10, 531-541.

Yanagihara, N. (1967b): Hoarseness: investigation of the physiological mechanisms. Ann Otol Rhinol Laryngol 76, 472-488.

Yanagihara, N. and Koike, Y. (1967): The regulation of sustained phonation. Folia Phoniatr 19, 1-18.

Yanagihara, N. and Leden. H. von (1967): Respiration and phonation (the functional examination of laryngeal disease). Folia Phoniatr 19, 153-166.

Yanagihara, N. (1970): Aerodynamic examination of the laryngeal function. Stud Phonologica, 45-51.
Yanof, H.M., Rosen, A.L., McDonald, N.M. and McDonald, D.A. (1963): A critical study of the response of manometers to forced oscillations. Phys Med Biol B, 407-422.
Yanof, H.M. (1965): Biomedical electronics. F.A. Davis Comp, Philadelphia.

Table 4-3. Table of characteristic values of the regression lines from all measuring series from normal subjects. Subject number, sex, interval in months between successive measuring series, and the number of instances of phonation per measuring series have been represented together with the intensity range and the intensity value for the middle of the range. The characteristic values have been given for flow, pressure, and efficiency. The last column records the difference in dB at I_m (E_{rel}) between each efficiency regression line and the calculated reference regression line, see 3.6.

Subject No.	male/female	interval months	No. of phonations	Intensity-range	I_m	AIR FLOW RATE				SUBGLOTTIC PRESSURE				EFFICIENCY				E_{rel}
						b	a	e.s.d.e.		b	a	e.s.d.e.		b	a	e.s.d.e.		
				dB	dB	$x10^{-2}$			ml/s	$x10^{-2}$			kPa	$x10^{-2}$			$x10^{-5}$	dB
1	M	0	34	60 - 92	76	2.122	0.758	0.16	235	3.29	-2.3	0.11	0.81	4.587	-3.006	0.2	3	-2.2
1	M	1	89	64 - 88	76	1.155	1.372	0.13	177	2.746	-2.193	0.18	0.78	6.099	-4.02	0.24	4.1	-0.8
1	M	10	46	60 - 93	76.5	1.51	1.2	0.13	227	2.428	-2.022	0.15	0.68	6.063	-4.019	0.21	4.2	-1.1
2	M	0	45	60 - 100	80	1.83	1.033	0.1	199	2.385	-2.081	0.09	0.67	6.033	-3.393	0.13	10.	0.8
2	M	4	45	65 - 100	82.5	1.067	1.589	0.12	295	2.271	-2.003	0.11	0.74	6.662	-4.427	0.2	11.	-0.4
2	M	7	60	61 - 102	81.5	0.9	1.727	0.13	288	2.434	-2.154	0.14	0.67	6.266	-4.413	0.21	10.5	-0.3
2	M	0	87	61 - 103	82	1.317	1.37	0.15	282	2.25	-1.992	0.14	0.71	6.433	-4.218	0.21	11.4	+0.2
2	M	21	49	58 - 99	78.5	1.449	1.215	0.12	225	2.333	-2.084	0.1	0.56	6.218	-3.972	0.19	8.1	0.5
2	M	11	28	66 - 95	80.5	1.105	1.429	0.07	208	2.1	-1.859	0.11	0.68	6.795	-4.41	0.15	11.5	0.8
2	M	3	30	62 - 99	80.5	0.618	1.892	0.09	245	2.006	-1.746	0.12	0.74	7.376	-4.987	0.16	8.9	-0.3
3	M	0	41	59 - 103	81	1.673	1.02	0.14	237	2.764	-2.419	0.08	0.66	5.563	-3.442	0.18	11.6	0.5
3	M	11	95	59 - 105	82	2.052	0.653	0.19	217	2.387	-2.033	0.12	0.84	5.561	-3.461	0.21	12.6	0.2
4	M	0	21	60 - 90	75	1.187	1.55	0.13	266	1.893	-1.533	0.09	0.77	6.92	-4.842	0.15	2.2	-2.8
5	V	0	22	58 - 101	79.5	0.761	1.947	0.09	356	1.683	-1.465	0.07	0.75	7.556	-5.323	0.13	4.8	-2.3
8	M	0	19	64 - 92	78	1.718	1.125	0.12	292	2.456	-1.997	0.1	0.83	5.825	-3.969	0.18	3.8	-2.5
8	M	4	29	68 - 92	80	1.889	0.913	0.1	266	3.12	-2.473	0.12	1.06	4.991	-3.281	0.12	5.1	-2.4
9	V	0	27	64 - 92	78	0.192	2.069	0.13	166	3.093	-2.517	0.06	0.79	6.714	-4.394	0.14	7	0.2
9	V	6	26	60 - 91	75.5	1.11	1.476	0.1	206	2.95	-2.418	0.11	0.64	5.94	-3.899	0.18	3.9	-0.8
10	V	0	17	63 - 96	79.5	0.623	1.794	0.13	195	2.653	-2.172	0.12	0.87	6.724	-4.464	0.18	7.6	-0.4
10	V	22	16	60 - 94	77	1.59	0.988	0.17	166	1.754	-1.586	0.1	0.58	6.647	-4.243	0.26	7.5	1.2
11	V	0	30	70 - 97	83.5	2.26	0.476	0.24	230	2.872	-2.449	0.13	0.89	4.868	-2.867	0.27	15.8	0.3
12	M	0	57	61 - 94	77.5	0.241	2.377	0.27	366	2.809	-2.488	0.14	0.49	6.95	-4.73	0.33	4.5	-1.3
12	M	11	43	60 - 85	72.5	0.828	1.733	0.21	215	2.726	-2.559	0.21	0.26	6.446	-4.015	0.28	4.6	1.9
13	M	0	25	70 - 104	87	0.681	1.902	0.1	312	4.535	-3.735	0.12	1.62	4.784	-3.008	0.18	14.2	-2.4
13	M	0	49	59 - 108	83.5	1.027	1.556	0.13	259	3.423	-2.201	0.13	1.48	5.55	-3.707	0.18	8.5	-2.4
15	V	0	38	65 - 95	80	-0.192	2.366	0.17	163	2.042	-1.764	0.09	0.74	8.149	-5.443	0.17	11.9	1.3
16	M	0	47	60 - 93	76.5	0.409	2.006	0.17	209	2.463	-2.026	0.07	0.72	7.128	-4.821	0.19	4.3	-1
16	M	6	43	59 - 94	76.5	0.97	1.43	0.11	149	2.249	-1.841	0.11	0.76	6.781	-4.43	0.15	5.7	0.3
17	M	0	73	62 - 103	82.5	1.922	0.819	0.13	253	2.389	-1.929	0.14	1.1	5.689	-3.73	0.21	9.2	-1.5
17	M	1	78	59 - 103	81	1.863	0.809	0.14	208	2.073	-1.671	0.1	1.02	6.064	-3.979	0.2	8.6	-0.8
18	M	0	51	60 - 94	77	2.285	0.661	0.15	263	2.608	-2.11	0.09	0.79	5.107	-3.392	0.21	3.5	-2.2
18	M	0	65	61 - 95	78	1.79	1.005	0.13	252	2.281	-1.849	0.1	0.85	5.929	-3.997	0.19	4.2	-2
19	V	0	37	82 - 102	92	2.381	0.38	0.1	372	2.753	-2.403	0.15	1.35	4.866	-2.818	0.12	45.6	-0.5
21	M	0	25	65 - 97	81	-0.126	2.466	0.15	231	2.577	-2.065	0.08	1.05	7.549	-5.242	0.16	7.5	-1.4
22	V	0	43	71 - 90	80.5	1.858	0.926	0.07	264	2.593	-2.121	0.1	0.92	5.549	-3.646	0.12	6.6	-1.6
24	M	0	39	62 - 88	75	-0.136	2.334	0.07	171	1.579	-1.587	0.1	0.4	8.557	-5.589	0.12	6.8	2
25	M	0	34	63 - 94	78.5	1.288	1.292	0.09	201	2.67	-2.441	0.1	0.45	6.043	-3.692	0.15	11.3	2
26	V	0	18	64 - 88	76	2.776	0.062	0.21	148	1.9	-1.563	0.07	0.76	5.35	-3.34	0.21	5.1	0.1
26	V	5	21	62 - 89	75.5	1.325	1.147	0.18	140	1.982	-1.659	0.1	0.69	6.693	-4.329	0.21	5.3	0.6
27	V	0	24	68 - 86	77	-0.99	3.006	0.1	175	0.851	-0.929	0.17	0.53	10.14	-6.917	0.13	7.8	1.3
27	V	2	36	66 - 97	81.5	-0.413	2.615	0.1	189	0.982	-0.899	0.15	0.8	9.432	-6.556	0.16	13.5	0.9
28	V	0	46	60 - 105	82.5	0.702	1.733	0.11	205	2.67	-2.221	0.12	0.96	6.629	-4.352	0.16	13.1	0.1
28	V	5	39	60 - 102	81	1.714	0.667	0.13	114	3.613	-2.996	0.12	0.85	4.673	-2.513	0.2	18.7	2.6
29	V	0	32	64 - 96	80	1.15	1.136	0.17	114	2.537	-2.137	0.11	0.78	6.313	-3.841	0.2	16.2	2.6
30	V	0	36	60 - 97	78.5	1.49	0.656	0.21	67	2.93	-2.465	0.2	0.68	5.581	-3.032	0.27	22.3	4.9
30	V	5	28	65 - 93	79	2.451	-0.054	0.10	76	2.811	-2.412	0.11	0.64	4.738	-2.375	0.17	23.4	4.8
31	M	0	30	64 - 94	79	0.190	1.326	0.14	130	2.593	-2.183	0.17	0.73	6.409	-3.983	0.2	12	1.9
32	V	0	17	60 - 86	73	1.766	0.812	0.26	126	1.902	-1.547	0.14	0.69	6.331	-4.106	0.35	3.3	0.1
35	M	0	27	65 - 100	82.5	0.76	1.778	0.17	257	2.158	-1.774	0.09	1.02	7.077	-4.845	0.18	9.8	-1.2
35	M	0	38	60 - 106	83	0.634	1.921	0.11	280	2.318	-1.969	0.11	0.9	7.048	-4.793	0.16	11.4	-0.8
38	M	0	24	61 - 90	75.5	1.69	0.998	0.13	190	2.37	-2.06	0.14	0.54	5.934	-3.779	0.13	5	0.4
40	V	0	11	65 - 90	77.5	0.411	1.908	0.13	168	2.835	-2.346	0.08	0.71	6.713	-4.402	0.18	6.8	0.4
41	V	0	18	60 - 80	70	1.343	1.251	0.12	155	2.062	-1.83	0.07	0.41	6.595	-4.261	0.15	2.3	0.4
44	M	0	48	58 - 88	73	3.333	0.027	0.13	289	2.899	-2.409	0.12	0.51	3.768	-2.459	0.16	2	-2.1
46	M	0	38	60 - 87	73.5	1.269	1.337	0.16	186	2.03	-1.745	0.17	0.56	6.701	-4.433	0.13	3.1	-0.4
47	M	0	23	58 - 89	73.5	1.293	1.303	0.09	179	2.87	-2.378	0.12	0.54	5.837	-3.766	0.17	3.3	-0.1
49	V	0	37	60 - 102	81	0.998	1.298	0.13	128	2.481	-2.085	0.07	0.84	6.521	-4.053	0.14	16.9	2.2
49	V	1	32	63 - 88	75.5	0.051	2.005	0.17	110	1.855	-1.726	0.11	0.47	8.095	-5.12	0.23	9.8	3.3
50	V	0	19	68 - 88	78	0.172	2.162	0.06	198	2.548	-2.203	0.06	0.61	7.28	-4.8	0.07	7.6	0.6
50	V	2	25	65 - 87	76	-0.197	2.288	0.12	138	2.542	-2.258	0.08	0.47	7.655	-4.871	0.15	8.8	2.5
51	V	0	44	62 - 95	78.5	1.347	1.131	0.16	154	2.406	-2.048	0.07	0.69	6.247	-3.924	0.16	9.5	1.2
52	V	0	23	66 - 93	79.5	1.945	1.038	0.07	384	2.324	-1.956	0.08	0.78	5.731	-3.923	0.1	4.3	-2.8
54	V	0	27	62 - 92	77	0.577	1.745	0.13	155	1.822	-1.448	0.12	0.9	7.601	-5.138	0.19	5.2	-0.4
55	M	0	46	60 - 92	76	1.493	1.299	0.1	271	2.376	-2.144	0.15	0.46	6.13	-3.995	0.17	4.6	-0.3
56	V	0	30	60 - 88	74	1.219	1.217	0.16	132	1.921	-1.808	0.11	0.41	6.861	-4.251	0.23	6.7	2.6
60	M	0	30	60 - 92	76	1.611	0.992	0.09	165	2.897	-2.271	0.12	0.85	5.492	-3.562	0.12	4.1	-0.8
61	M	0	34	64 - 103	83.5	1.637	0.98	0.14	222	2.342	-1.841	0.1	1.3	6.021	-3.979	0.19	11.2	-1.2
61	M	1	46	74 - 99	86.5	1.147	1.428	0.07	263	2.575	-2.1	0.07	1.34	6.278	-4.169	0.12	18.3	-1
62	M	0	35	65 - 104	84.5	0.192	2.221	0.1	241	3.181	-2.564	0.19	1.33	6.627	-4.498	0.12	12.7	-1.3
62	M	0	50	63 - 104	83.5	0.032	2.387	0.12	259	3.315	-2.634	0.15	1.36	6.653	-4.593	0.14	9.2	-2.1
62	M	0	19	72 - 101	86.5	0.079	2.321	0.08	245	4.25	-3.371	0.23	2.02	5.671	-3.791	0.22	13	-2.5
63	M	0	82	62 - 93	77.5	1.819	0.879	0.1	195	3.338	-2.897	0.11	0.49	4.842	-2.824	0.14	8.5	1.4

Table 4-4. Table of characteristic values of the regression lines from normal subjects with more than one measuring series. (For legends see Table 4-3). The 27 calculated differences, between the successive values of E_{rel} from each subject in this table, have been used for establishing the significance limits, see 4.3.3.2.

Subject No.	male/female	interval months	No. of phonations	Intensity-range	$\bar{I}_m$	AIR FLOW RATE				SUBGLOTTIC PRESSURE				EFFICIENCY				E_{rel}
						b	a	e.s.d.e.		b	a	e.s.d.e.		b	a	e.s.d.e.		
				dB	dB	$x10^{-2}$			ml/s	$x10^{-2}$			kPa	$x10^{-2}$			10^{-5}	dB
1	M	0	34	60 - 92	76.2	2.122	0.758	0.16	238	3.29	-2.593	0.11	0.82	4.587	-3.006	0.2	3.1	-2.2
1	M	1	89	64 - 88	76.2	1.155	1.372	0.13	178	2.746	-2.193	0.18	0.79	6.099	-4.02	0.24	4.2	-0.8
1	M	10	46	60 - 93	76.2	1.51	1.2	0.13	224	2.428	-2.022	0.15	0.67	6.063	-4.019	0.21	4	-1.1
2	M	0	45	60 - 100	80.8	1.583	1.033	0.1	205	2.385	-2.081	0.09	0.7	6.033	-3.793	0.13	12.1	0.8
2	M	4	45	65 - 100	80.8	1.067	1.589	0.12	283	2.271	-2.003	0.11	0.68	6.662	-4.427	0.2	9	-0.4
2	M	7	60	61 - 102	80.8	0.9	1.727	0.13	284	2.434	-2.154	0.14	0.65	6.666	-4.413	0.21	9.4	-0.3
2	M	0	87	61 - 103	80.8	1.317	1.37	0.15	272	2.25	-1.992	0.14	0.67	6.433	-4.218	0.21	9.5	-0.2
2	M	21	49	58 - 99	80.8	1.449	1.215	0.12	243	2.333	-2.084	0.1	0.63	6.218	-3.972	0.19	11.3	0.5
2	M	11	28	66 - 95	80.8	1.105	1.429	0.07	210	2.1	-1.859	0.11	0.69	6.795	-4.41	0.15	12	0.8
2	M	3	30	62 - 99	80.8	0.618	1.892	0.09	246	2.006	-1.746	0.12	0.75	7.376	-4.987	0.16	9.4	-0.3
3	M	0	41	59 - 103	81.5	1.673	1.02	0.14	242	2.764	-2.419	0.08	0.68	5.563	-3.442	0.18	12.4	0.5
3	M	11	95	59 - 105	81.5	2.052	0.653	0.19	212	2.387	-2.033	0.12	0.82	5.561	-3.461	0.21	11.8	0.3
8	M	0	19	64 - 92	79	1.718	1.125	0.12	304	2.456	-1.997	0.1	0.88	5.825	-3.969	0.18	4.3	-2.5
8	M	4	29	68 - 92	79	1.889	0.913	0.1	254	3.12	-2.473	0.12	0.98	4.991	-3.281	0.12	4.6	-2.2
9	V	0	27	64 - 92	76.8	0.192	2.069	0.13	165	3.093	-2.517	0.06	0.72	6.714	-4.394	0.14	5.8	0.2
9	V	6	26	60 - 91	76.8	1.11	1.476	0.1	213	2.95	-2.418	0.11	0.7	5.94	-3.899	0.18	4.6	-0.8
10	V	0	17	63 - 96	78.3	0.623	1.794	0.13	191	2.653	-2.172	0.12	0.8	6.724	-4.464	0.18	6.3	-0.4
10	V	22	16	60 - 94	78.3	1.599	0.988	0.17	174	1.754	-1.586	0.1	0.61	6.647	-4.243	0.26	9.1	1.2
12	M	0	57	61 - 94	75	0.241	2.377	0.27	361	2.809	-2.488	0.14	0.42	6.95	-4.73	0.33	3	-1.5
12	M	11	43	60 - 85	75	0.828	1.733	0.21	226	2.726	-2.559	0.21	0.31	6.446	-4.015	0.28	6.6	1.9
13	M	0	25	70 - 104	85.3	0.681	1.902	0.1	304	4.535	-3.735	0.12	1.36	4.784	-3.008	0.18	11.8	-2.1
13	M	0	49	59 - 108	85.3	1.027	1.556	0.13	270	3.423	-2.689	0.13	1.7	5.55	-3.707	0.18	10.6	-2.6
16	M	0	47	60 - 93	76.5	0.409	2.006	0.17	209	2.463	-2.026	0.07	0.72	7.128	-4.821	0.19	4.3	-1
16	M	6	43	59 - 94	76.5	0.97	1.43	0.11	149	2.249	-1.841	0.11	0.76	6.781	-4.43	0.15	5.7	0.3
17	M	0	73	62 - 103	81.8	1.922	0.819	0.13	246	2.389	-1.929	0.14	1.06	5.689	-3.73	0.21	8.4	-1.4
17	M	1	78	59 - 103	81.8	1.863	0.809	0.14	215	2.073	-1.671	0.1	1.06	6.064	-3.979	0.2	9.6	-0.8
18	M	0	51	60 - 94	77.5	2.285	0.661	0.15	270	2.608	-2.11	0.09	0.81	5.107	-3.392	0.21	3.7	-2.3
18	M	0	65	61 - 95	77.5	1.79	1.005	0.13	247	2.281	-1.849	0.1	0.83	5.929	-3.997	0.19	4	-1.9
26	V	0	18	64 - 88	75.8	2.776	0.062	0.21	147	1.9	-1.563	0.07	0.75	5.325	-3.34	0.21	5	0.1
26	V	5	21	62 - 89	75.8	1.325	1.147	0.18	142	1.982	-1.659	0.1	0.7	6.693	-4.329	0.21	5.6	0.6
27	V	0	24	68 - 86	79.3	-0.99	3.006	0.1	166	0.851	-0.929	0.17	0.56	10.14	-6.917	0.13	13.3	2.2
27	V	2	36	66 - 97	79.3	-0.413	2.615	0.1	193	0.982	-0.899	0.15	0.76	9.432	-6.556	0.16	8.4	0.2
28	V	0	46	60 - 105	81.8	0.702	1.733	0.11	203	2.67	-2.221	0.12	0.92	6.629	-4.352	0.16	11.7	0.1
28	V	5	39	60 - 102	81.8	1.714	0.667	0.13	117	3.613	-2.996	0.12	0.91	4.673	-2.513	0.2	20.4	2.5
30	V	0	36	60 - 97	78.8	1.49	0.656	0.21	68	2.93	-2.465	0.2	0.7	5.581	-3.032	0.27	23.2	4.9
30	V	5	28	65 - 93	78.8	2.451	-0.054	0.18	75	2.811	-2.412	0.11	0.63	4.738	-2.375	0.17	22.9	4.9
35	M	0	27	65 - 100	82.8	0.765	1.778	0.17	258	2.158	-1.774	0.09	1.03	7.077	-4.845	0.18	10.3	-1.1
35	M	0	38	60 - 106	82.8	0.634	1.921	0.11	279	2.318	-1.969	0.11	0.89	7.048	-4.793	0.16	11	-0.8
49	V	0	37	60 - 102	78.3	0.998	1.298	0.13	120	2.481	-2.085	0.07	0.72	6.521	-4.053	0.14	11.3	2.1
49	V	1	32	63 - 88	78.3	0.051	2.005	0.17	111	1.855	-1.726	0.11	0.53	8.095	-5.12	0.23	16.5	3.8
50	V	0	19	68 - 88	77	0.172	2.162	0.06	197	2.548	-2.203	0.06	0.57	7.28	-4.8	0.07	6.4	0.5
50	V	2	25	65 - 87	77	-0.197	2.288	0.12	137	2.542	-2.258	0.08	0.5	7.655	-4.871	0.15	10.5	2.6
61	M	0	34	64 - 103	85	1.637	0.98	0.14	235	2.342	-1.841	0.1	1.41	6.021	-3.979	0.19	13.8	-1.3
61	M	1	46	74 - 99	85	1.147	1.428	0.07	253	2.575	-2.1	0.07	1.23	6.278	-4.169	0.12	14.7	-1
62	M	0	35	65 - 104	84.8	0.192	2.221	0.1	242	3.181	-2.564	0.19	1.36	6.627	-4.498	0.16	13.2	-1.3
62	M	0	50	63 - 104	84.8	0.032	2.387	0.12	259	3.315	-2.634	0.15	1.5	6.653	-4.593	0.14	11.2	-2.1
62	M	0	19	72 - 101	84.8	0.079	2.321	0.08	244	4.25	-3.371	0.23	1.71	5.671	-3.791	0.22	10.4	-2.4

Table 5-2. Table of characteristic values of the regression lines from all measuring series with 64 patients.
(For legends see Table 4-3.)

Patient No.	male/female	interval months	No. of phonations	Intensity-range	I_m	AIR FLOW RATE				SUBGLOTTIC PRESSURE				EFFICIENCY				E_{rel}
						b	a	e.s.d.e.		b	a	e.s.d.e.		b	a	e.s.d.e.		
				dB	dB	$x10^{-2}$			ml/s	$x10^{-2}$			kPa	$x10^{-2}$			$x10^{-5}$	dB
1	V	0	24	60 - 78	69	0.621	2.084	0.05	325	1.627	-0.92	0.08	1.59	7.751	-6.004	0.11	0.2	-9.1
2	V	0	25	63 - 76	69.5	0.054	2.598	0.13	432	0.674	-0.476	0.17	0.98	9.272	-6.962	0.26	0.3	-8
2	V	27	17	61 - 81	71	1.064	2.078	0.17	681	-0.209	0.136	0.09	0.97	9.145	-7.055	0.17	0.3	-9.4
3	V	0	31	60 - 85	72.5	0.589	1.813	0.12	174	2.07	-1.696	0.09	0.64	7.342	-4.958	0.19	2.3	-1.1
3	V	6	61	64 - 95	79.5	0.243	2.19	0.12	242	2.704	-2.174	0.07	0.95	7.052	-4.857	0.18	5.6	-1.7
4	V	0	31	63 - 80	71.5	2.691	0.367	0.06	196	0.421	-0.411	0.03	0.78	6.889	-4.798	0.06	1.3	-2.8
4	V	4	43	65 - 90	77.5	1.022	1.67	0.09	290	1.963	-1.627	0.08	0.78	7.015	-4.884	0.1	3.6	-2.4
4	V	9	72	62 - 96	79	0.423	2.053	0.08	244	1.728	-1.488	0.07	0.75	7.849	-5.406	0.1	6.2	-0.9
6	V	0	17	62 - 78	70	1.249	1.593	0.07	293	1.726	-1.385	0.06	0.67	7.025	-5.049	0.11	0.7	-4.5
7	V	0	50	67 - 84	75.5	0.636	2.247	0.08	534	1.678	-1.204	0.08	1.15	7.685	-5.883	0.1	0.8	-7.4
8	V	0	35	63 - 88	75.5	1.068	1.726	0.1	341	1.37	-0.914	0.09	1.32	7.562	-5.653	0.15	1.1	-6.1
8	V	3	36	64 - 88	76	1.031	1.457	0.09	174	2.797	-2.178	0.1	0.89	6.172	-4.12	0.15	3.7	-1.3
9	V	0	24	57 - 78	67.5	2.273	1.016	0.1	355	4.281	-2.952	0.11	0.87	3.447	-2.905	0.18	0.3	-7.3
9	V	24	21	38 - 65	51.5	1.6	2.013	0.1	688	2.092	-1.347	0.1	0.54	6.308	-5.507	0.14	0	-14
10	V	0	46	62 - 93	77.5	-0.058	2.632	0.15	386	1.114	-0.789	0.18	1.19	8.945	-6.683	0.2	1.8	-5.4
10	V	4	37	68 - 97	82.5	0.31	2.411	0.09	464	1.631	-1.092	0.33	1.8	8.059	-6.16	0.42	3.1	-6.2
10	V	15	32	60 - 92	76	0.26	2.342	0.19	346	1.378	-1.058	0.07	0.98	8.363	-6.125	0.22	1.7	-4.7
11	M	0	43	61 - 85	73	0.867	1.916	0.08	354	2.331	-1.716	0.12	0.97	6.802	-5.041	0.17	0.8	-5.8
11	M	24	33	62 - 93	77.5	0.559	2.064	0.08	314	1.943	-1.465	0.08	1.1	7.497	-5.44	0.15	2.3	-4.2
12	M	0	32	65 - 80	72.5	1.796	0.931	0.06	171	1.134	-0.548	0.03	1.88	7.07	-5.224	0.07	0.8	-5.7
12	M	19	42	67 - 93	80	0.432	1.647	0.11	98	1.879	-1.303	0.1	1.58	7.689	-5.185	0.12	9.3	0.2
13	M	0	35	62 - 80	71	0.054	2.449	0.11	307	3.627	-2.731	0.09	0.7	6.319	-4.559	0.15	0.8	-4.5
14	V	0	26	63 - 74	68.5	2.166	0.183	0.26	46	0.69	-0.58	0.16	0.78	7.143	-4.444	0.21	2.8	2.3
14	V	6	72	62 - 96	79	0.423	2.053	0.08	244	1.728	-1.488	0.07	0.75	7.849	-5.406	0.1	6.2	-0.9
15	M	0	27	72 - 90	81	0.744	1.734	0.1	217	2.456	-1.57	0.16	2.63	6.8	-5.006	0.11	3.2	-5.1
15	M	2	44	67 - 94	80.5	1.011	3.355	0.17	348	1.79	-1.382	0.1	1.14	9.221	-6.813	0.21	4.1	-3.7
16	M	0	27	65 - 85	75	-0.734	3.24	0.1	489	1.831	-1.265	0.07	1.28	8.903	-6.816	0.12	0.7	-7.7
18	M	0	32	73 - 88	80.5	0.441	2.205	0.13	364	1.867	-1.341	0.1	1.45	7.692	-5.705	0.11	3.1	-5
18	M	21	16	63 - 87	75	-0.957	3.084	0.07	232	2.198	-1.672	0.12	0.95	8.759	-6.253	0.14	2.1	-3.2
19	V	0	44	68 - 78	73	2.151	0.764	0.08	216	0.717	-0.604	0.07	0.83	7.132	-5.001	0.09	1.6	-3
19	V	4	52	69 - 87	78	0.185	1.976	0.08	132	2.774	-2.156	0.06	1.02	7.04	-4.66	0.1	6.8	0.1
19	V	11	54	65 - 85	75	2.004	0.755	0.11	181	2.977	-2.242	0.11	0.98	5.019	-3.354	0.13	2.6	-2.2
20	V	0	45	70 - 86	78	0.475	2.09	0.1	289	1.448	-1.085	0.08	1.11	8.078	-5.846	0.14	2.8	-3.7
20	V	14	51	75 - 94	84.5	-0.258	2.463	0.1	176	-0.033	0.205	0.05	1.5	10.291	-7.508	0.1	15.4	-0.5
21	M	0	53	64 - 93	78.5	0.578	2.17	0.09	420	2.383	-1.804	0.1	1.17	7.04	-5.207	0.15	2.1	-5.4
21	M	4	32	64 - 83	73.5	-0.597	2.96	0.11	332	1.606	-1.069	0.11	1.29	8.991	-6.732	0.17	0.8	-6.6
23	M	0	43	65 - 87	76	0.428	2.011	0.15	217	1.837	-1.435	0.09	0.92	7.735	-5.417	0.1	2.9	-2.3
23	M	12	31	63 - 76	69.5	1.106	2.151	0.08	832	0.34	-0.137	0.09	1.26	8.555	-6.856	0.12	0.1	-11.9
24	V	0	36	66 - 91	78.5	0.643	2.017	0.13	333	2.348	-1.794	0.12	1.12	7.009	-5.064	0.2	2.7	-4.2
24	V	13	40	59 - 87	73	3.244	-0.072	0.16	197	2.433	-1.869	0.13	0.81	4.324	-2.9	0.24	1.8	-2.5
25	M	0	44	69 - 92	80.5	0.853	1.791	0.11	300	2.883	-1.999	0.09	2.1	6.265	-4.634	0.14	2.6	-5.7
25	M	13	24	70 - 89	79.5	1.596	0.937	0.11	161	1.58	-1.094	0.14	1.45	6.824	-4.684	0.2	5.5	-1.8
26	V	0	42	65 - 95	80	0.77	1.71	0.09	212	1.842	-1.467	0.11	1.01	7.388	-5.084	0.18	6.7	-1.2
26	V	14	39	70 - 88	79	2.74	0.072	0.1	172	3.855	-2.958	0.12	1.22	3.406	-1.955	0.18	5.4	-1.5
27	V	0	54	65 - 92	78.5	0.374	1.642	0.14	86	1.948	-1.61	0.07	0.83	7.678	-4.872	0.15	14.3	3
27	V	13	63	60 - 93	76.5	1.023	1.407	0.1	155	2.618	-1.982	0.14	1.05	6.359	-4.266	0.19	4	-1.3
28	M	0	56	67 - 97	82	0.615	1.881	0.07	243	2.669	-2.173	0.1	1.04	6.715	-4.548	0.15	9.1	-1.2
29	V	0	35	64 - 81	72.5	2.803	4.41	0.18	239	2.442	-1.953	0.11	0.66	10.361	-7.298	0.19	1.6	-2.6
29	V	21	42	65 - 89	77	-0.304	2.686	0.08	283	1.069	-1.026	0.11	0.63	9.235	-6.501	0.16	4.1	-1.5
30	V	0	51	63 - 91	77	1.698	1.293	0.16	399	2.398	-1.901	0.1	0.88	5.904	-4.232	0.21	2.1	-4.5
30	V	14	33	70 - 88	79	2.003	0.874	0.13	286	2.419	-2.002	0.1	0.81	5.578	-3.713	0.18	4.9	-1.9
31	M	0	48	63 - 88	75.5	1.534	0.988	0.11	140	1.924	-1.442	0.11	1.02	6.543	-4.387	0.12	3.6	-1.1
31	M	14	52	65 - 91	78	1.176	1.364	0.08	191	2.186	-1.705	0.06	1	6.639	-4.5	0.12	4.8	-1.4
32	M	0	58	63 - 90	76.5	1.5	1.249	0.11	249	2.906	-2.024	0.11	1.58	5.595	-4.066	0.18	1.6	-5.1
32	M	13	35	69 - 90	79.5	-0.539	2.589	0.11	145	2.044	-1.619	0.12	1.01	8.495	-5.811	0.17	8.8	0.2
33	M	0	36	71 - 88	79.5	0.55	1.933	0.09	234	1.103	-0.425	0.11	2.83	8.348	-6.349	0.14	1.9	-6.3
33	M	18	22	63 - 81	72	1.461	0.997	0.09	112	1.592	-0.997	0.06	1.41	6.946	-4.841	0.12	1.4	-2.8
33	M	7	23	64 - 81	72.5	0.357	1.739	0.16	100	1.927	-1.293	0.09	1.27	7.716	-5.287	0.21	2	-1.7
34	M	0	28	65 - 90	77.5	0.144	2.622	0.11	541	1.916	-1.474	0.09	1.03	7.94	-5.989	0.11	1.5	-6.3
34	M	1	46	62 - 91	76.5	1.105	1.829	0.07	472	1.652	-1.232	0.1	1.08	7.243	-5.438	0.14	1.3	-6.3
34	M	2	81	60 - 91	75.5	1.627	1.318	0.19	352	2.13	-1.78	0.1	0.67	6.243	-4.379	0.25	2.2	-3.3
34	M	8	65	60 - 95	77.5	1.615	1.325	0.17	377	2.199	-1.741	0.12	0.92	6.186	-4.425	0.21	2.3	-4.2
35	V	0	26	65 - 83	74	0.256	2.086	0.13	188	2.579	-2.05	0.07	0.72	7.165	-4.877	0.14	2.7	-1.4
36	M	0	53	67 - 86	76.5	1.279	1.471	0.15	281	1.569	-0.995	0.07	1.6	7.152	-5.317	0.16	1.4	-5.7
36	M	13	49	57 - 93	75	1.117	1.54	0.13	239	1.111	-0.861	0.06	0.94	7.771	-5.52	0.14	2	-3.2
37	V	0	55	60 - 95	77.5	1.539	1.014	0.24	161	2.269	-1.923	0.1	0.69	6.192	-3.932	0.28	7.3	0.7
38	V	0	41	64 - 90	77	0.74	1.63	0.08	158	1.851	-1.531	0.09	0.79	7.408	-4.94	0.15	5.8	0.1
38	V	17	36	61 - 85	73	0.642	1.698	0.1	147	2.083	-1.67	0.1	0.71	6.772	-4.533	0.2	2.6	-0.9
39	M	0	37	72 - 85	78.5	1.925	0.776	0.06	194	2.802	-2.025	0.08	1.5	5.273	-3.592	0.12	3.5	-3.1
39	M	17	27	60 - 74	67	0.862	1.847	0.08	266	1.903	-1.39	0.06	0.77	7.179	-5.258	0.11	0.4	-5.7
40	M	0	38	63 - 95	79	-0.204	2.679	0.12	329	1.395	-0.979	0.08	1.33	8.808	-6.541	0.14	2.6	-4.7
40	M	17	49	61 - 88	74.5	1.434	1.34	0.13	256	1.99	-1.443	0.12	1.1	6.576	-4.739	0.16	1.4	-4.4
41	M	0	26	62 - 92	77	2.12	1.015	0.06	444	2.58	-1.98	0.1	1.02	5.3	-3.876	0.13	1.6	-5.5
41	M	14	26	60 - 87	73.5	1.932	1.091	0.16	324	2.143	-1.741	0.1	0.68	5.925	-4.191	0.19	1.5	-3.7
42	V	0	30	62 - 89	75.5	1.112	1.836	0.07	474	1.768	-1.243	0.15	1.24	7.119	-5.434	0.21	0.9	-7.2
42	V	13	46	64 - 94	79	1.615	1.216	0.06	310	2.997	-2.418	0.11	0.89	5.388	-3.639	0.15	4.1	-2.7
43	M	0	51	65 - 98	81.5	-0.524	2.74	0.15	206	2.303	-1.891	0.13	0.97	8.221	-5.69	0.18	10.3	-0.3
44	V	0	42	67 - 89	78	0.936	1.94	0.16	468	2.711	-2.036	0.06	1.2	6.352	-4.745	0.19	1.6	-6.1
44	V	2	60	64 - 88	76	1.174	1.769	0.11	459	2.672	-2.042	0.08	0.97	6.153	-4.568	0.15	1.3	-5.9
44	V	9	68	61 - 91	76	0.669	1.961	0.2	295	3.072	-2.385	0.16	0.89	6.259	-4.417	0.3	2.2	-3.6
45	V	0	39	70 - 92	81	-1.079	3.278	0.1	254	2.286	-1.907	0.07	0.88	8.793	-6.212	0.12	8.1	-1
45	V	11	40	62 - 82	72	-1.25	3.289	0.1	244	2.157	-1.783	0.08	0.59	9.093	-6.346	0.12	1.6	-2.4
46	V	0	42	65 - 79	72	2.079	0.791	0.09	194	1	-0.755	0.12	0.92	6.92	-4.876	0.15	1.3	-3.4
46	V	12	55	69 - 88	78.5	0.968	1.392	0.08	142	3.356	-2.552	0.15	1.21	5.675	-3.68	0.19	6	-0.8
47	V	0	45	61 - 90	75.5	1.596	1.048	0.13	179	2.446	-1.815	0.11	1.08	5.958	-4.073	0.2	2.7	-2.4
47	V	7	60	54 - 94	74	1.097	1.423	0.14	172	2.157	-1.797	0.1	0.63	6.746	-4.467	0.2	3.4	-0.4
48	M	0	37	63 - 88	75.5	2.088	0.609	0.1	153	1.425	-1.014	0.12	1.15	6.487	-4.435	0.17	2.9	-2
48	M	12	47	61 - 87	74	1.165	1.352	0.12	164	2.758	-2.097	0.15	0.88	6.077	-4.096	0.21	2.5	-1.7
49	M	0	39	61 - 85	73	1.083	1.646	0.09	273	2.637	-2.097	0.13	0.67	6.28	-4.39	0.18	1.6	-3.1
49	M	12	59	59 - 93	76	2.27	0.644	0.11	234	2.759	-2.276	0.16	0.66	4.971	-3.208	0.17	3.7	-1.3
50	M	0	11	73 - 77	75	2.456	0.469	0.04	205	3.248	-2.545	0.08	0.78	4.292	-2.762	0.11	2.9	-1.8
51	M	0	46	64 - 88	76	1.926	1.205	0.09	467	2.731	-1.93	0.09	1.4	5.342	-4.115	0.16	0.9	-7.5
51	M	10	61	59 - 87	73	1.232	1.618	0.14	329	2.258	-1.639	0.16	1.02	6.509	-4.82	0.18	0.9	-5.7
52	V	0	58	62 - 88	75	3.458	-0.118	0.16	299	2.684	-2.07	0.11	0.88	3.858	-2.653	0.17	1.7	-3.9
52	V	11	30	60 - 91	75.5	1.62	1.256	0.11	302	1.867	-1.562	0.14	0.7	6.513	-4.536	0.19	2.4	-2.8
53	V	0	60	64 - 95	79.5	0.767	1.634	0.08	175	1.662	-1.237	0.09	1.21	7.571	-5.238	0.12	6	-1.4
54	V	0	40	64 - 92	78	-0.343	2.656	0.12	245	1.871	-1.477	0.07	0.96	8.472	-6.021	0.13	3.9	-2.3
54	V	9	59	61 - 101	81	1.904	0.933	0.22	299	2.176	-1.562	0.15	1.59	5.92	-4.211	0.34	3.8	-4.3
54	V	12	39	61 - 88	74.5	1.134	3.35	0.23	320	1.768	-1.276	0.14	1.1	9.366	-6.915	0.35	1.2	-5.4
55	V	0	52	64 - 102	83	0.774	2.067	0.11	512	2.331	-1.724	0.11	1.62	6.895	-5.184	0.19	3.5	-6
55	V	11	69	60 - 93	76.5	1.812	1.019	0.09	254	2.98	-2.263	0.09	1.04	5.208	-3.596	0.12	2.4	-3.4
56	V	0	55	70 - 88	79	1.282	2.004	0.05	1039	1.472	-1.22	0.08	0.88	7.246	-5.626	0.13	1.3	-7.9
56	V	15	22	68 - 87	77.5	-0.638	3.102	0.1	406	1.9	-1.282	0.14	1.55	8.737	-6.66	0.2	1.3	-6.8
57	V	0	32	62 - 83	72.5	1.384	3.1	0.14	125	0.891	-0.504	0.08	1.39	10.492	-7.436	0.19	1.5	-3
58	M	0	76	58 - 94	76	1.559	1.327	0.11	325	2.371	-1.986	0.11	0.65	6.07	-4.181	0.14	2.7	-2.6
58	M	8	38	60 - 97	78.5	1.23	1.321	0.06	193	2.5	-2.173	0.1	0.62	6.27	-3.988	0.13	8.6	0.8
58	M	2	53	61 - 102	81.5	1.428	1.244	0.1	256	2.079	-1.777	0.11	0.83	6.493	-4.308	0.15	9.6	-0.6
59	V	0	36	61 - 97	79	0.299	1.771	0.18	102	3.137	-2.542	0.1	0.86	6.564	-4.07	0.19	13	2.3
60	V	0	50	61 - 85	73	1.179	1.708	0.14	370	1.04	-0.428	0.1	2.15	7.78	-6.121	0.2	0.4	-9.5
60	V	3	43	58 - 85	71.5	1.04	1.661	0.18	254	1.085	-0.644	0.15	1.35	7.875	-5.858	0.28	0.6	-6.4
61	M	0	50	65 - 94	79.5	-0.348	2.834	0.12	361	1.31	-0.916	0.08	1.34	9.038	-6.759	0.18	2.7	-4.9
61	M	7	25	73 - 96	84.5	-0.07	2.43	0.06	235	1.728	-1.335	0.09	1.33	8.342	-5.936	0.13	13	-1.2
62	V	0	48	59 - 97	78	0.961	1.559	0.12	204	2.113	-1.756	0.11	0.78	6.926	-4.644	0.15	5.7	-0.6
63	V	0	24	61 - 80	70.5	0.967	1.94	0.05	418	3.778	-2.832	0.13	0.68	5.254	-3.948	0.14	0.6	-5.9
63	V	27	20	68 - 80	74	0.206	2.32	0.13	297	1.537	-1.201	0.15	0.86	8.256	-5.959	0.26	1.4	-4.2
64	M	0	46	65 - 95	80	0.706	1.896	0.13	289	2.29	-1.812	0.13	1.05	7.004	-4.925	0.19	4.8	-2.7
64	M	3	42	60 - 93	76.5	1.27	1.451	0.15	265	2.562	-2.004	0.11	0.9	6.167	-4.288	0.19	2.7	-3
65	M	0	44	61 - 81	71	-0.255	2.702	0.04	332	2.655	-1.885	0.11	1	7.6	-5.658	0.11	0.5	-6.4
66	M	0	16	59 - 80	69.5	0.26	2.393	0.06	375	0.553	0.217	0.12	3.99	9.186	-7.451	0.13	0.1	-13.5
67	M	0	26	63 - 82	72.5	2.846	0.158	0.1	167	0.899	-0.503	0.04	1.41	6.254	-4.496	0.11	1.1	-4.3